TARDEC

---TECHNICAL REPORT---

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Magneto-Rheological Fluid Semi-active Suspension Performance Testing

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Mobility testing was conducted on two HMMWVs at the U.S. Army Yuma Proving Grounds by the U.S. Army Tank-automotive Research, Development and Engineering Center (TARDEC), and Rod Millen Special Vehicles (RMSV) of Huntington Beach, California January 7-9 2003. One of the vehicles tested was a standard HMMWV and the second was a civilian 1992 Hummer with a magneto-rheological fluid (MR) semi-active suspension system that was designed and installed on the vehicle by RMSV. The purpose of the tests was to evaluate the possible performance benefits of the MR fluid suspension system. Ride quality performance was quantified over three separate cross-country courses. Each vehicleŸs driver limited speed was also measured over discrete half-round obstacles of 4, 6, and 8-inch heights. Vehicle maneuverability was also evaluated by testing over a lane-change course and a slalom course at a variety of vehicle speeds. Limited vehicle roll down tests were also conducted to get a comparison of the rolling resistance of the two vehicles.

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Vehicle maneuverability was also evaluated by testing over a lane-change course and a slalom course at a variety of vehicle speeds. Limited vehicle roll down tests were also conducted to get a comparison of the rolling resistance of the two vehicles.

INTRODUCTION
This report documents the testing of MagnetoRheological fluid Optimized Active Damper Suspension (MROADS) system on commercial Hummer vehicle as shown in Figure 1. The vehicle modifications and testing were conducted under a Small Business Innovative Research contract (SBIR) with Rod Millen Special Vehicles.. Under this SBIR, RMSV designed and fabricated an MR fluid suspension strut and the associated control system. RMSV also installed the system on a civilian 1992 Hummer and performed vehicle shakedown testing. TARDEC then sponsored the formal mobility testing of the modified Hummer (along with a similar High Mobility Multi-purpose Wheeled Vehicle or HMMWV as shown in Figure 2) at Yuma Proving Grounds (YPG) in Yuma, Arizona.

Figure 1 - - MR Fluid MROADS 1992 Hummer

This MR fluid, semiactive suspension design effort, to produce the MROADS, was conducted under the Small Business Innovative Research (SBIR) program. Under the first phase of the SBIR contract, RMSV investigated available MR fluids and a variety of shock absorber design approaches based on such fluids. A commercially available MR fluid was selected and RMSV designed and laboratory tested a prototype MR fluid based shock absorber. The successful laboratory testing of this unit, led to the SBIR Phase 2 contract being awarded for the development of a more meaningful demonstration.

The purpose of the Phase 2 contract was to develop a complete MR fluid based, semiactive suspension system for application on a HMMWV. The complete semiactive system would include the MR fluid based actuators, all required vehicle state sensors, the vehicle controller, and all necessary electrical interface components. The system was to be designed, developed, and installed on a Hummer by RMSV. Evaluation and testing of the completed semiactive Hummer was to be funded and carried out by the US Army at Yuma Proving Grounds in Yuma, Arizona. The purpose of the Phase 2 effort was to optimize the cross-country ride of the resulting semiactive suspension vehicle while also improving the vehicle stability and handling. The measure of success of the program was to be in terms of the amount of improvement in cross-country ride that the MR fluid based semiactive suspension Hummer exhibited over the standard HMMWV.

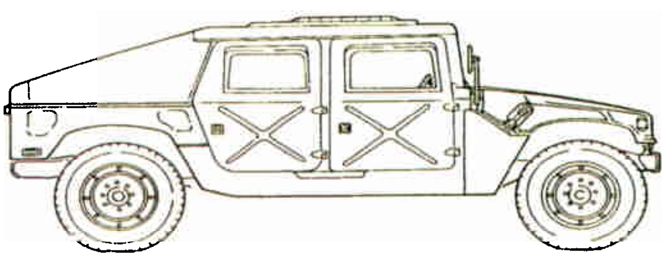

Figure 2 - High Mobility Multi-Purpose Wheeled Vehicle (HMMWV)

RMSV was selected for their participation in this program based upon their experience and success in designing high performance off-road vehicles and suspension systems. They utilized a commercially available MR fluid and designed and fabricated their own MR fluid shock absorber and semiactive suspension system.

The following sections discuss briefly the past semiactive suspension efforts at TARDEC and the MR fluid based semiactive suspension developed and tested on the Hummer. This is followed by a description of the test and evaluation plan and the subsequent test results for this MR fluid semiactive Hummer and the baseline HMMWV as carried out at YPG in January 2003.

SEMIACTIVE SUSPENSION PAST RESULTS

The US Army has been investigating the incorporation of semiactive suspension systems in its combat vehicle designs for the last decade. Semiactive suspension, also sometimes referred to as adaptive or active damping, is a system that rapidly modulates the damping force of each shock absorber to improve vehicle ride and stability. A variety of vehicle motion sensors can be used as input to the semiactive suspension controller to permit the judicious use of available vehicle damping forces. The sensors used may include chassis and wheel vertical accelerometers, chassis pitch and roll rate sensors, a steering angle sensor, and suspension travel and/or rate sensors.

A semiactive suspension requires virtually no additional power from the vehicle to vary the vehicle damping. All that is required (in addition to the controller power) is to switch the damping force rapidly between different values. The relative motion across each suspension member can only be resisted by that wheel's damper. In other words, for the semiactive damper, the only control option is in terms of whether to resist the relative motion or not (and how strongly). The power required to resist the relative motion is lost as heat (as in a standard damper). Active suspension, in contrast, can enhance or oppose suspension relative motion, and therefore requires additional power from the vehicle to provide the control force (although in the resisting mode this could be done with a controllable damper as in the semiactive case).

The results of each of TARDEC's semiactive suspensions have been quite positive. A 22 ton experimental tracked vehicle (called the Mobility Technology Test Bed or MTTB by its creator) was tested over a variety of cross-country terrains. Five different configurations of the semiactive MTTB were tested against its equivalent normally damped system [1]. A 30-40 % increase in cross-country ride limiting speed (as measured at the driver's seat) was recorded for each of the five vehicle configuration pairs.

Spurred on by the significant success of the semiactive suspension on the MTTB, the M1A1 and the M2 (i.e. the Abrams and the Bradley) vehicles were then modeled with semiactive suspension systems [2]. The simulations of these vehicle concepts demonstrated a similar percentage performance gain over the standard vehicles for most of the cross-country terrains. At the very rough terrain (the 3.5 inch rms), however, the improvement was a bit less.

Following the simulation study, an M2 Bradley vehicle was subsequently modified to include a semiactive suspension system. The semiactive damping was incorporated into a previously developed in-arm hydropneumatic suspension system and installed on a Bradley vehicle. This vehicle also underwent a thorough set of performance tests along with a standard Bradley [3]. The semiactive Bradley again showed about a 30 % increase in ride limiting speed over the standard Bradley over a wide variety of cross-country terrain profiles.

The MTTB employed hydraulic damping with a computer controlled damping orifice to achieve its variable damping. The Bradley system, on the other hand, used a set of friction discs to supply the damping force. The normal force applied to the friction discs was controlled through a small hydraulic actuator.

In the 1993-94 time periods, an experimental controllable shock absorber using an electrorheological (ER) fluid was also developed and demonstrated in the laboratory [4]. The ER shock absorber had an unacceptable size to force ratio and the fluid experience significant settling problems.

The capabilities and advances of magnetorheological (MR) fluids came to light in the mid 90s and made an MR fluid damper seem more practical than its ER counterpart. Thus a development effort to develop and demonstrate an MR fluid based semiactive suspension system on a HMMWV was initiated in 1999. This paper reports the performance results obtained from this development effort.

MR FLUID SEMIACTIVE SUSPENSION

An MR fluid is a material that responds to an applied magnetic field with a significant change in its rheological behavior [5]. The properties of such a fluid can change from a free-flowing, low viscosity fluid, to a near solid when a magnetic field is applied. The change in properties takes place in a few milliseconds and is fully reversible. The yield strength is controllable by the strength of the magnetic field.

A typical MR fluid contains about 20-40% by volume of microscopic iron particles (typically 3-5 microns). These particles are suspended in a carrier fluid such as water, mineral oil, or synthetic oil. The resulting fluid will be as much as 80% iron by weight. Various additives are incorporated in the MR fluid to improve lubricity, reduce wear, and improve the suspension of the iron particles in the fluid.

MR fluid shock absorbers have been used as adjustable linear shocks in racing applications for several years and have also found commercial application in heavy truck seat suspensions and in washing machines. More recently, an MR fluid based semiactive suspension system has been developed and marketed by Delphi Automotive [6]. This system is called the MagneRide system and is consists of four MR fluid based actuators, sensors, and a controller. This MR fluid based semiactive suspension was introduced on the 2002 Cadillac and has expanded to the Corvette for the 2003 model year.

A more complete description of the MROADS design and installation are included in the RMSV Final Report [7]. The following sections describe the test and evaluation plan and the subsequent test results for this MR fluid semiactive Hummer and the baseline HMMWV as carried out at YPG in January 2003.

TEST PLAN

The U.S. Army Tank-automotive Research and Development Center has long been involved in the development and evaluation of advanced suspension technologies. The major focus of these efforts is to increase the cross-country mobility performance of combat vehicles while not degrading the vehicle's stability and maneuverability. The objective of this formal testing was to quantify the relative performance, in terms of ride quality, shock response, and maneuverability, of the magnetorheological fluid (MRF) semi-active suspension on the Hummer vehicle, with respect to a comparative HMMWV with a passive suspension system. The specific tests designed to produce these quantities are summarized below with the full description of the test plan included in Appendix A.

RIDE QUALITY

The performance criterion for ride quality is based on absorbed power. Absorbed power is a measure of a human's tolerance to vibration. The absorbed power theory was developed, tested, and quantified in the late 60s at TACOM and is recorded by references [8-11]. Absorbed power is a time average of frequency weighted root-mean-square (rms) accelerations. The recognized (documented in references cited above) ride limiting absorbed power for an average driver was determined to be approximately 6 watts for a medium short duration (maybe 3-10 minutes).

For this program three separate ride quality courses were used at YPG. These courses are labeled as RMS courses 3, 4, and 5 and have corresponding roughness indices of 1.5, 2.0, and 3.4 inches rms. The general layout of the RMS courses is shown in Appendix A - figure A1. The courses are hard packed gravel and are maintained and periodically resurveyed by YPG to maintain their roughness content. A photograph of RMS course 5 is shown in Figure 3.

Figure 3 - Terrain RMS Course 5 at YPG

Each vehicle (the MRF Hummer and the passive HMMWV) was run over a course at as near a constant speed as possible. The vertical acceleration was recorded at the base of the driver's seat and directly below the driver's torso. This vertical acceleration was then used to compute the driver's vertical absorbed power for that speed over that course. Generally the course was run in both directions at the same speed and the two drivers' absorbed powers were averaged. (Note that the absorbed power theory includes input for the driver's pitch and roll motion's and for the driver's feet. The criterion most generally used, however, employs only the driver's vertical absorbed power.) The vehicle speed is gradually increased on subsequent runs down the course to provide an accurate estimate of the vehicle driver's ride limiting speed on that course (i.e. the speed at which the driver received 6 watts of vertical absorbed power). This procedure is completed for courses with a variety of roughness levels and the ride limiting speed is plotted as a function of surface roughness.

SHOCK QUALITY

The vehicle's shock transmission performance is based on the peak vertical acceleration measured at the base of the driver's seat. The driver's acceleration is measured over a series of rigid half-round obstacles of increasing height. The general layout of the bump course used in the shock test is shown in Appendix A - figure A2. The course is a concrete surface with the appropriate half round obstacle bolted in place on the course. Each obstacle is traversed at increased vehicle speeds until the driver's shock limit is exceeded. The driver's shock limit is set at 2.5 g's, and the speed at which he experiences this 2.5 g limit is recorded for each obstacle. A plot of the 2.5 g shock limiting speed versus half-round obstacle height is then used to quantify the vehicle's shock performance.

MANEUVERABILITY

Maneuverability is defined here as the ability to safely execute various turning requirements at reasonable speeds. The maneuvers that are used to evaluate the maneuverability are the lane change and the slalom courses depicted in Appendix A - figures A3 and Appendix A - figure A4 respectively. The performance on these courses is measured in terms of the vehicle's roll motion and lateral acceleration as a function of vehicle velocity. A specific limit is not ascribed to these vehicle performance measures, but the relative performance between the MRF Hummer and the passive HMMWV can be made from the resulting data. The vehicle is driven through the courses at a constant speed (as near as possible) and the roll and lateral motions are recorded (as well as the steering input). The minimum and maximum values of roll rate and lateral acceleration are recorded for each vehicle speed that is run. This is done for both vehicle concepts and the results are plotted as a function of vehicle velocity.

VEHICLE SETUP AND INSTRUMENTATION

The magneto-rheological fluid semi-active suspension was installed by RMSV on a civilian 1992 Hummer. This hummer had a decal curb weight of 5930 lbs and a GVW of 10,300 lbs. The stated cg height was 32.5 inches. This semi-active suspension Hummer was instrumented by Rod Millen Special Vehicles and then shipped to Yuma Proving Grounds for testing.

The passive HMMWV, supplied by YPG, for comparison testing was a model M1037. This M1037 had a listed curb weight of 5424 lbs and a GVW of 8660 lbs. The listed height of the cg for this vehicle was 28.4 inches. Ballast was added to both of the vehicles to give them each approximately the same total weight and to also keep them comparable to the results of the earlier electromechanical (EM) active suspension tests and the subsequent low-bandwidth active, compressible fluid suspension tests [12-13]. The individual wheel loadings for the MRF Hummer and the passive HMMWV are shown in Figures 4 and 5.

For this particular test the contractor, Rod Millen Special Vehicles, instrumented the test vehicle and did the data collection themselves. Yuma Proving Grounds instrumented and did the data collection for the passive vehicle. This caused some difficulty when trying to analyze the data for comparison. The sensors that were used were not identical or positioned in the same locations on each vehicle. The sampling rates and filtering frequencies used were not the same either. Something that may have helped with this discrepancy would be to have taken pictures of all of the sensors on both vehicles, but this was not considered until after the fact.

In the execution of previous Compressible Fluid Suspension tests that TARDEC recently performed at YPG [13], Yuma Proving Grounds personnel instrumented both the test and the passive vehicles. This made data analysis much easier for comparison because the sensors used were identical. It is strongly recommended that for all future tests organized through the Mobility area here at TARDEC, that both the test vehicle and the passive vehicle be instrumented by the same people, preferably by the instrumentation group at the testing facility.

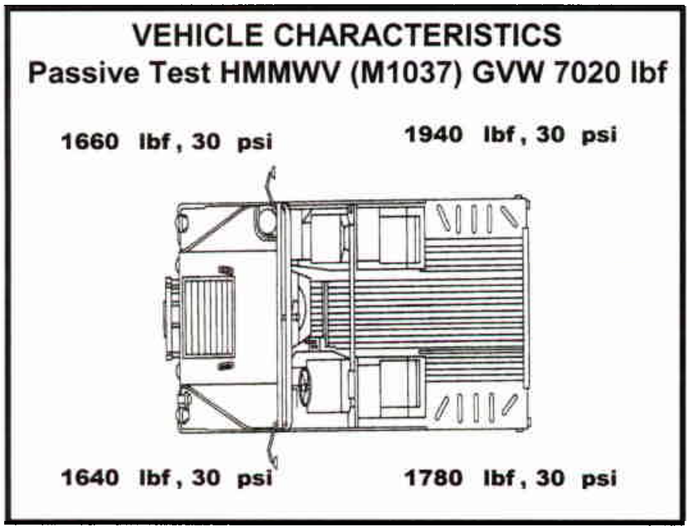

Figure 4 – Passive HMMWV Loads

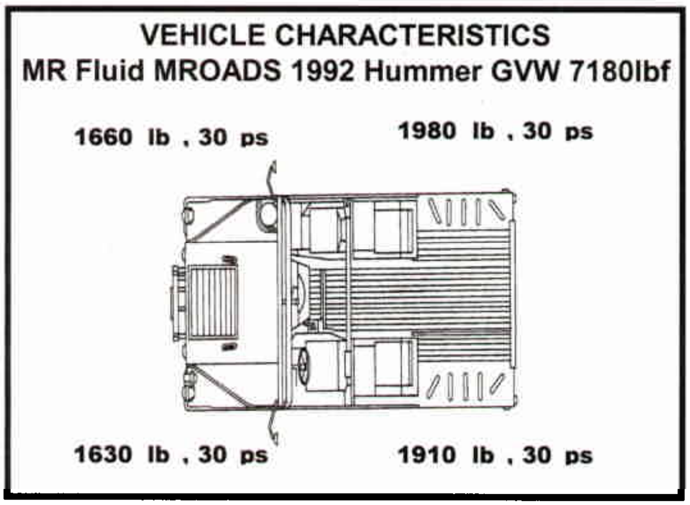

Figure 5 – MR Fluid Hummer Loads

The details of the particular sensors used are included in Appendix C and in Appendix D. The three angular rates and linear accelerations were recorded at approximately the cg of the chassis. An additional vertical accelerometer was mounted on the suspension arm of each wheel to assess wheel accelerations, particularly over the half-round obstacles. Separate accelerometers were also mounted on the vehicle frame near each wheel position. A separate vertical accelerometer was also mounted at the frame cross member behind the driver's seat to be used in driver's shock and ride quality performance measurement. Suspension travel was also measured for each wheel with a string potentiometer. And finally a steering angle sensor and a vehicle speed sensor were included. The steering sensor data from the passive vehicle was also filtered with a 10 Hz low-pass filter because of excessive noise in the signal. The MROADS vehicle also measured load leveler pressure, shock temperature, and damper force at each wheel.

The data for the passive HMMWV was sampled at 500 Hz for all runs except the half-round obstacle shock tests. The sample rates for the various sensors on the MROADS Hummer are listed in Appendix D.

TEST PROGRAM

The testing was conducted at Yuma Proving Grounds (YPG) during the week of 7-9 January 2003. The complete test matrix is included as Appendix B. The test program utilized two professional test drivers from YPG and generally alternated vehicles and drivers in the test sequence (note the test matrix does not maintain the exact chronology of test runs for the passive and active systems within a given test). Generally speaking, the less severe tests, in terms of possible damage to vehicle hardware, were run first; however because of high winds the RMS ride quality tests was run first. The following day the weather was more cooperative so we were then able to perform the slalom and lane change tests with the half-round bump shock test being run the third day.

Overall the MROADS hardware performed very well throughout the testing. The MROADS Hummer data collection was done directly onto a laptop aboard the vehicle. This proved much more convenient than the use of removable data collection cards on the passive HMMWV. The use of the removable data collection cards necessitated periodic pauses in the testing to allow for off loading test data and spot-checking of the collected data to ensure the continued operation of all the sensors and the data acquisition system.

RESULTS

Appendix E includes the minimum and maximum steering and chassis angular sensor values for each of the "Lane Change" test runs. These results, along with the average vehicle speed for the run, are included for both the MROADS Hummer and the stock HMMWV.

Several of the more interesting comparisons between the two vehicles are included below in graphical form. Also the vertical accelerometer located on the cross member behind the driver's seat was used to calculate the driver's vertical absorbed power values which are used as the basis for the ride quality curves described below.

Ride Quality Performance

Three separate ride quality courses were exercised for this portion of the testing. These YPG courses are labeled RMS3, RMS4, and RMS5 and have surface roughness levels of 1.5, 2.0, and 3.4 inches root-mean-square (rms) respectively. These ride quality courses are predominately pitch-plane courses (i.e. they do not induce vehicle roll motion). Several different signals were considered of interest for these "ride quality" course tests. In the following plots the more severe of the two directions (north or south) at each speed is reported.

The vertical wheel accelerations that might typically be seen in cross-country operation were one such signal. Each vehicle had a vertical accelerometer mounted on the A-arm close to each wheel. Figures 6-8 compares the maximum and minimum vertical wheel accelerations at the right front wheel for each of the test vehicles over the RMS courses.

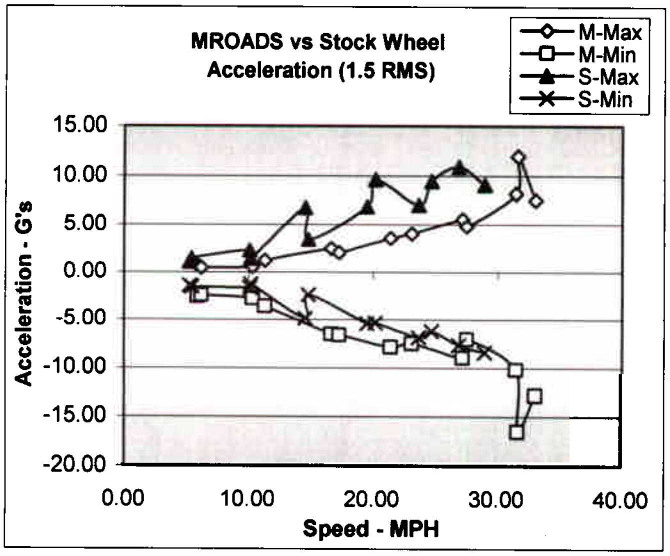

Figure 6- Comparison of Wheel Accelerations (1.5" RMS)

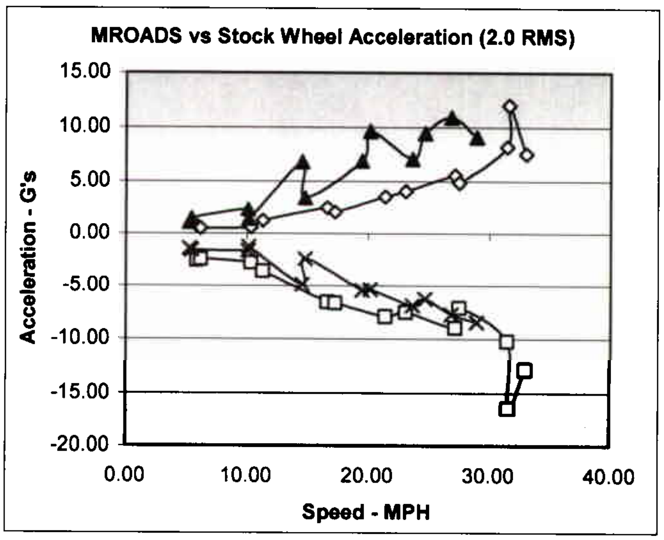

Figure 7- Comparison of Wheel Accelerations (2.0" RMS)

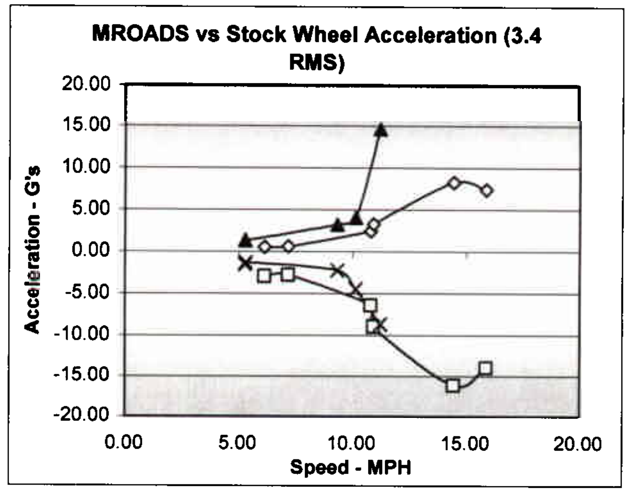

Figure 8 - Comparison of Wheel Accelerations (3.4" RMS)

Each figure contains the acceleration data as a function of vehicle speed for both vehicle concepts over one of the three RMS courses. There seems to be a little more maximum wheel acceleration for the stock HMMWV, but the difference is quite small. At the more extreme speeds, it can be noted, that both vehicles recorded vertical wheel accelerations of over 15 g's.

Suspension travel was also investigated for both vehicles over the RMS courses. Since the courses were not designed to induce vehicle roll, the suspension travel was analyzed only for the right side of the vehicles. Figures 9-12 show the minimum and maximum suspension travel experienced for the active and the passive vehicles over the 1.5" and 2.0" RMS course (the 3.4" course had a very limited number of runs on it and is not shown here). The maximum and minimum suspension travel was recorded for each run and the difference between this maximum and minimum is recorded as the wheel travel on these plots.

A close look at the wheel travel results over these rough cross-country courses reveals a couple of interesting features. First it should be noted that the MROADS Hummer was given 11 ½ total inches of suspension travel, whereas the stock HMWWV had only 8 inches on the front and 8 ¼ on the rear suspension. Also the rear spring on the Hummer was only about half as stiff as the rear spring on the HMMWV suspension. The stiffer rear spring for the HMMWV tends to keep the wheel travel smaller at the lower speeds than for the comparative Hummer runs (note particularly Figure 9). The MROADS Hummer in all cases tended to use more wheel travel than did the stock HMMWV and tended to find a range of wheel travel for each course and wheel position, and maintain that travel range for much of the vehicle speed range tested.

It is also interesting to note that the front wheel tended to use significantly more wheel travel than did the rear wheel. This was true for both test vehicles, over both cross-country courses and for each vehicle speed tested.

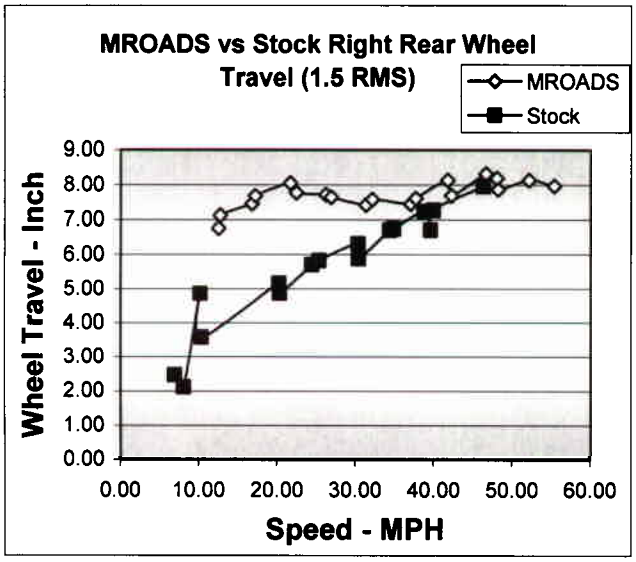

Figure 9 - Right Rear Wheel Travel (1.5" RMS)

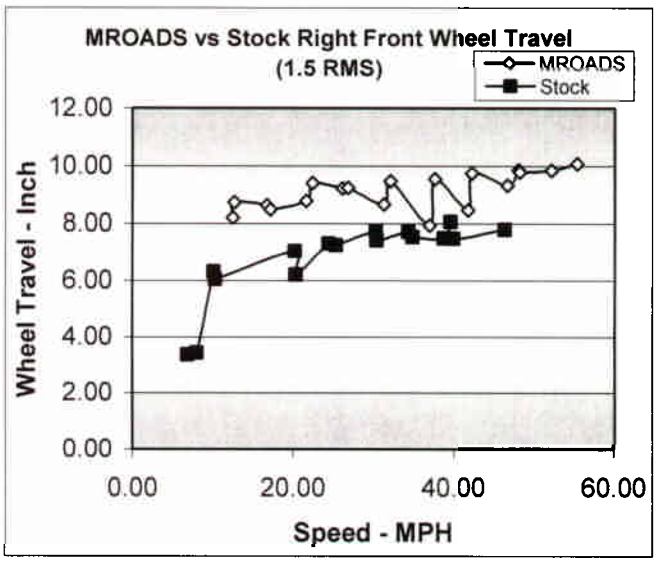

Figure 10 - Right Front Wheel Travel (1.5" RMS)

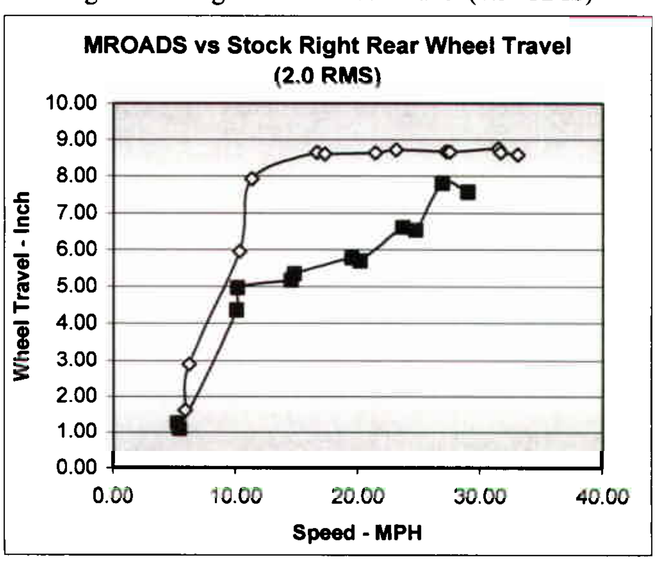

Figure 11 - Right Rear Wheel Travel (2.0" RMS)

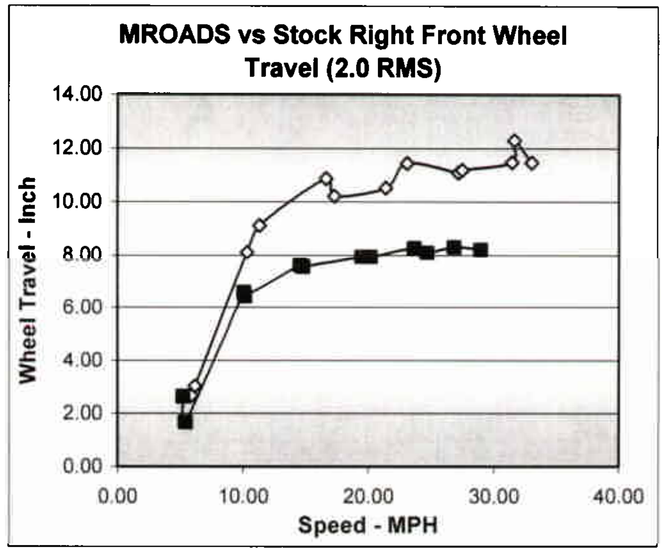

Figure 12 - Right Front Wheel Travel (2.0" RMS)

The peak chassis cg vertical accelerations are shown in Figures 13-15. The driver's seat is quite near the vehicle's longitudinal cg, making these measurements quite similar to what the driver would experience in the vertical direction. The minimum and maximum accelerations are reported for each run over each of the three RMS (or cross-country) courses that were tested over. The peak accelerations were quite similar for the two test vehicles at the more moderate speeds for each course. As the ride became more severe on each terrain, the peak accelerations for the stock HMMWV became more severe than did the same peak accelerations for the MROADS Hummer.

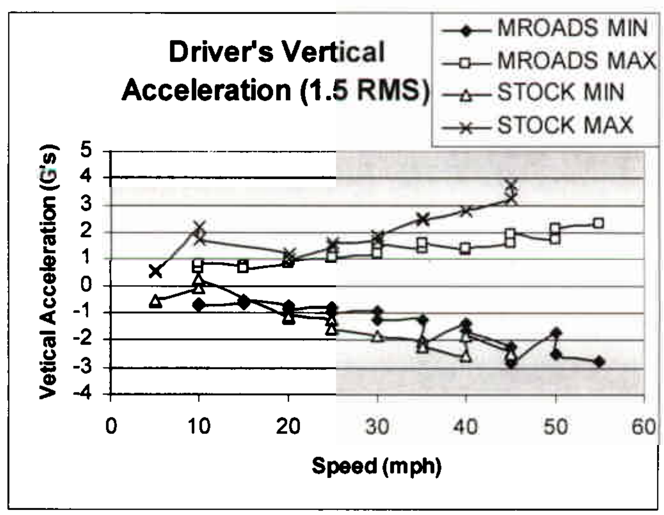

Figure 13 – Driver's Vertical Accelerations (1.5" RMS)

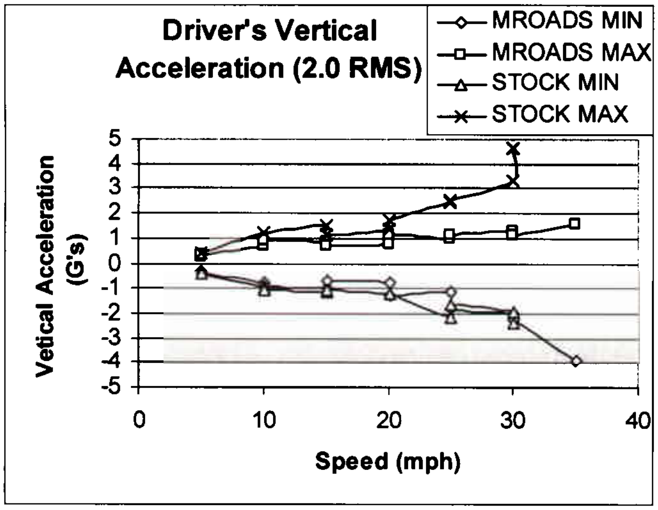

Figure 14 — – Driver's Vertical Acceleration (2.0" RMS)

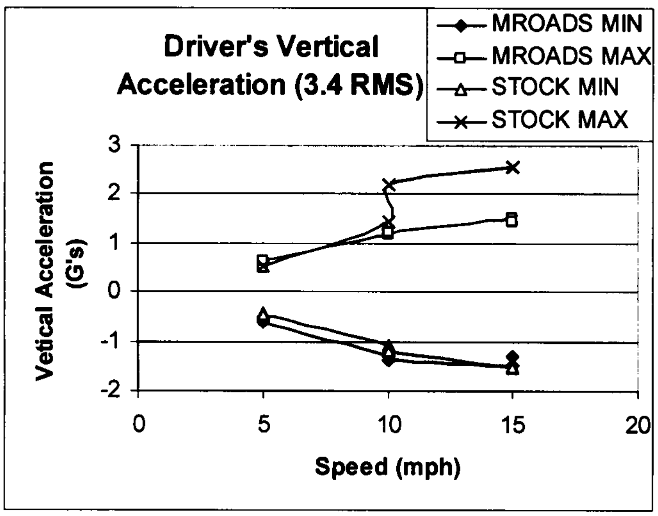

Figure 15 — – Driver's Vertical Acceleration (3.4" RMS)

Another measure of ride quality and platform stability over the RMS courses is depicted in Figures 16-18. Here the maximum chassis pitch rates (ignoring the sign of the pitch rate) for the MROADS Hummer and for the stock HMMWV are recorded for each RMS course. The pitch motion is about the same for the two vehicles over the 1.5" rms course (see Figure 16), but at the most severe run over the 2.0" rms course and for all tests over the 3.4" rms course, the stock HMMWV actually had a bit lower peak pitch velocity.

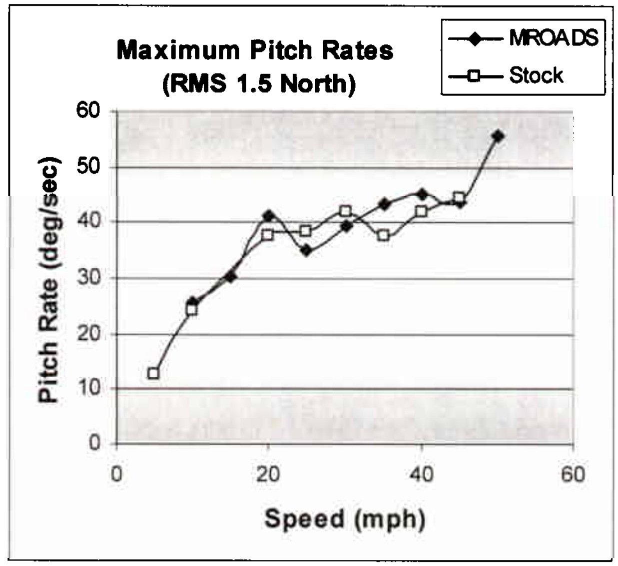

Figure 16 - Maximum Pitch Rates (1.5" RMS)

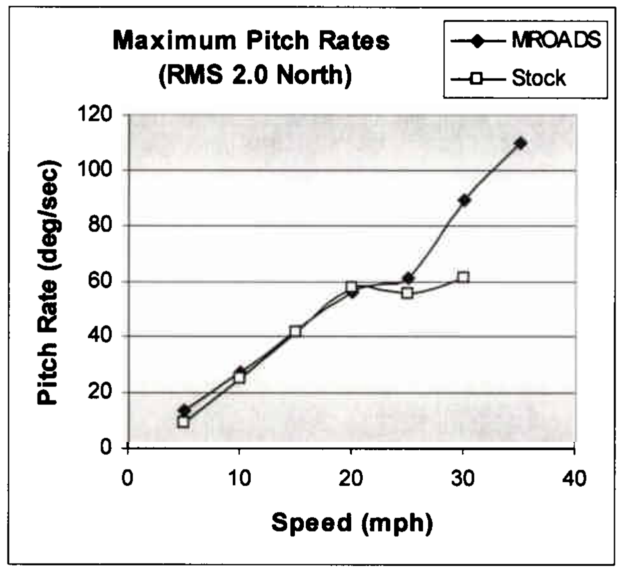

Figure 17 - Maximum Pitch Rates (2.0" RMS)

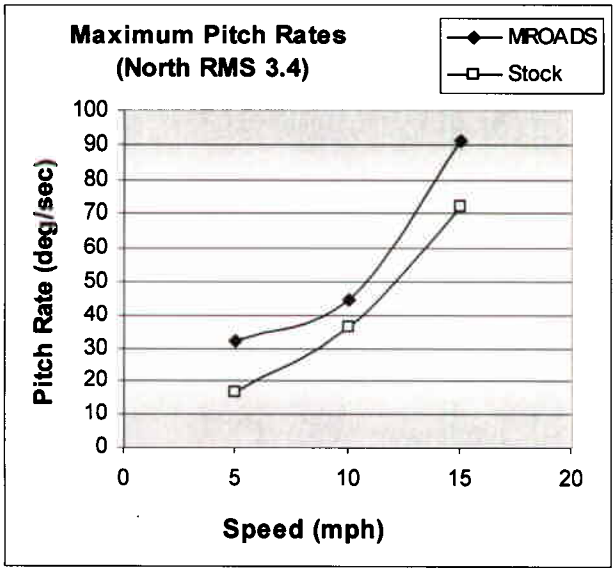

Figure 18 - Maximum Pitch Rates (3.4" RMS)

The ride quality of a vehicle is quantified in terms of the vehicle speeds over different RMS courses at which the vehicle's driver would experience 6 watts of vertical absorbed power. The driver's vertical absorbed power for each RMS course run was calculated and the results are plotted separately for the stock HMMWV and for the MROADS Hummer over each of the three RMS courses.

These driver absorbed power plots are shown in Figures 19-24. Each of these figures contains separate plots for the runs made in each of the two directions across the respective course. In general, it can be seen that the two directions produced quite similar absorbed power values. The two runs were averaged and an interpolated value was calculated (except for the passive HMMWV over the 3.4" rms course where a little extrapolation was employed based on the other absorbed power curves) for the 6 watt ride limiting speed over each terrain.

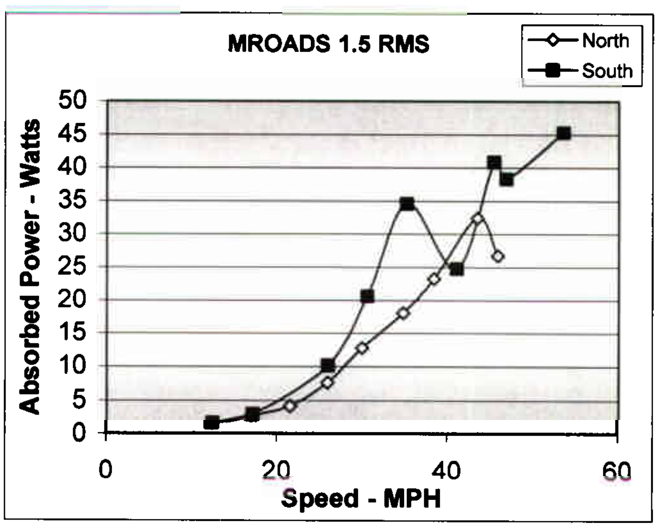

Figure 19 - MROADS 1.5" RMS

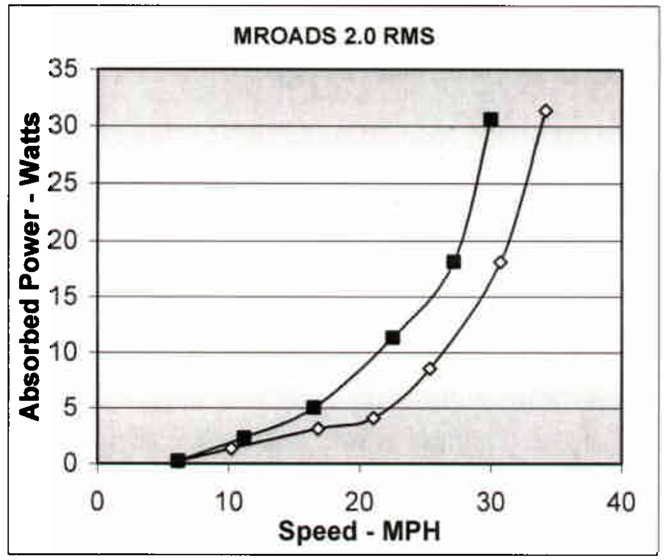

Figure 20 - MROADS 2.0" RMS

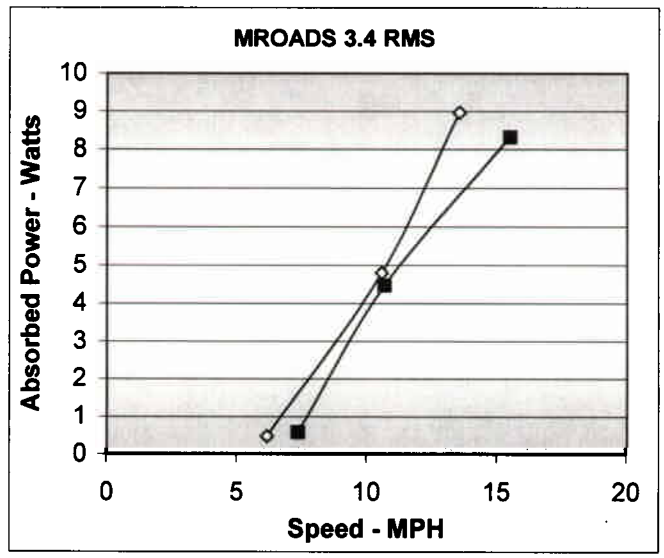

Figure 21 - MROADS 3.4" RMS

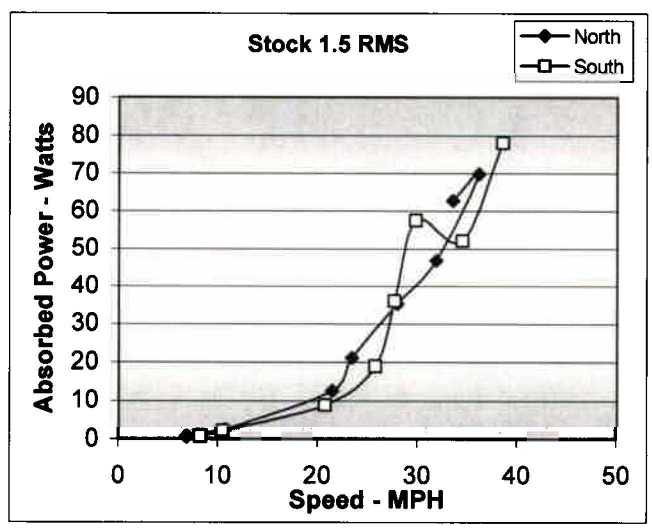

Figure 22 - Stock 1.5" RMS

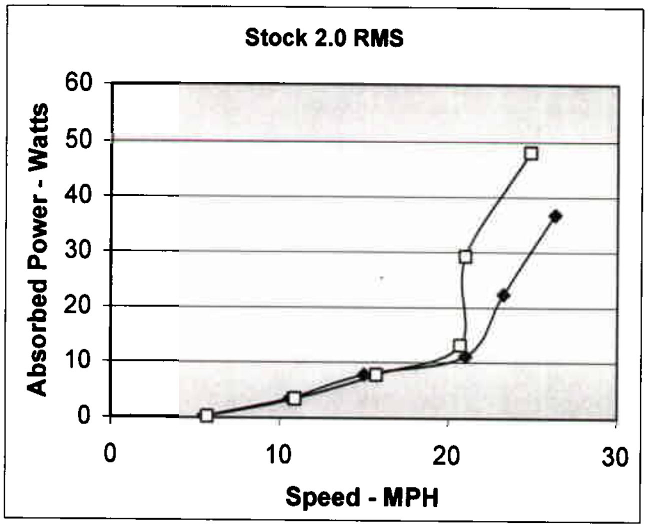

Figure 23 - Stock 2.0" RMS

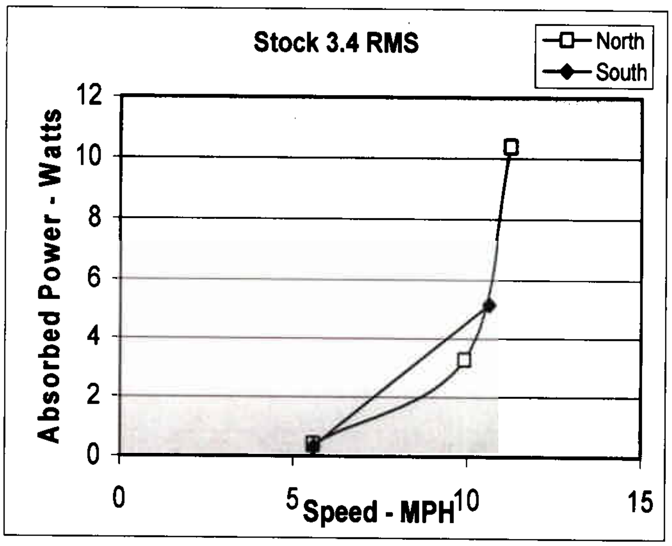

Figure 24 - Stock 3.4" RMS

The resulting ride limiting speed curves for the MROADS Hummer and the stock HMMWV are then shown in Figure 25. A fairly significant increase in ride limiting speed can be seen here for the MROADS Hummer over the passive HMMWV. The 1.5" rms terrain yielded about a 35% improvement for the MROADS Hummer, whereas the slightly rougher 2.0" rms course showed about a 25% increase in ride limiting speed. Only about a 10% increase in ride limiting speed was obtained over the more severe 3.4" rms course.

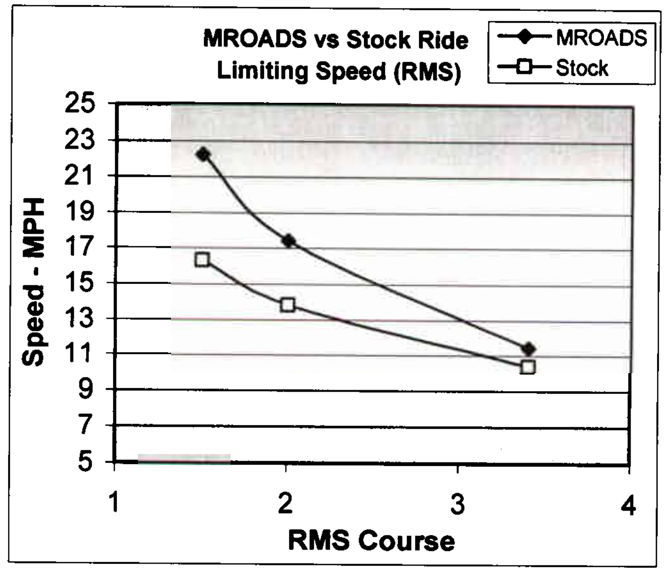

Figure 25 - Ride Limiting Speed

It should be noted that the MROADS test bed, the Hummer, was a commercial variant of the HMMWV and was not at all the same as the stock M1037 HMMWV which somewhat clouds the comparison. Also, as was previously noted, the MROADS Hummer was given an additional 3 to 3 ½ inches of suspension travel at each wheel which by itself should improve the vehicle ride quality. Also a load leveling system was implemented on the MROADS Hummer which would maintain the same jounce suspension travel regardless of vehicle load. The stock HMMWV would lose some of its original suspension jounce travel due to the vehicle's ballast load.

The passive (or stock) HMMWV that was used in the active Electromechanical Suspension (EMS) testing over the same RMS courses at YPG showed a couple of mph less for its ride limiting speed over both the 2.0" and the 3.4" rms courses [11]. These differences further compound the problem of comparing the MROADS Hummer performance to that of the stock HMMWV.

Shock Performance

The shock testing is based on the driver's tolerance to a single vertical acceleration input. The limiting shock level of vertical acceleration for the driver is considered to be 2.5 g's. The vehicle was tested over 4, 6, and 8 inch high, half round obstacles. The obstacles were made by cutting steel pipe in half lengthwise, and welding the half-round obstacles to steel plates. The half-round obstacles were bolted down on a concrete test area. Each obstacle was then negotiated at increasing speed until it was felt the shock was too severe to increase the speed further.

Figures 26-28 record the driver's vertical acceleration versus vehicle speed for each of the three obstacle heights. The driver's peak acceleration over the 4" obstacle was only slightly better (i.e. lower) for the MROADS Hummer than it was for the stock HMMWV. On the 6" and 8" obstacles this performance difference was more pronounced (again in favor of the Hummer). Of course the additional wheel travel of the Hummer could have been one of the leading reasons for this performance advantage.

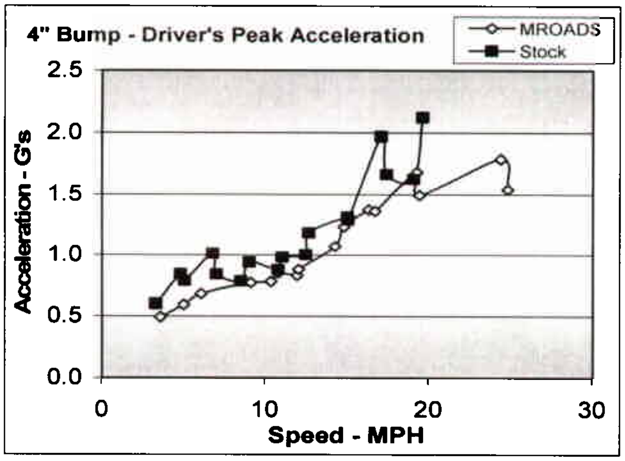

Figure 26 - 4" Bump Driver's Acceleration

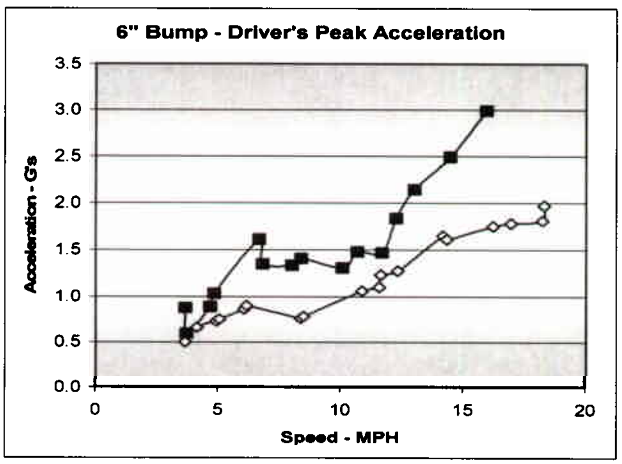

Figure 27 - 6" Bump Driver's Acceleration

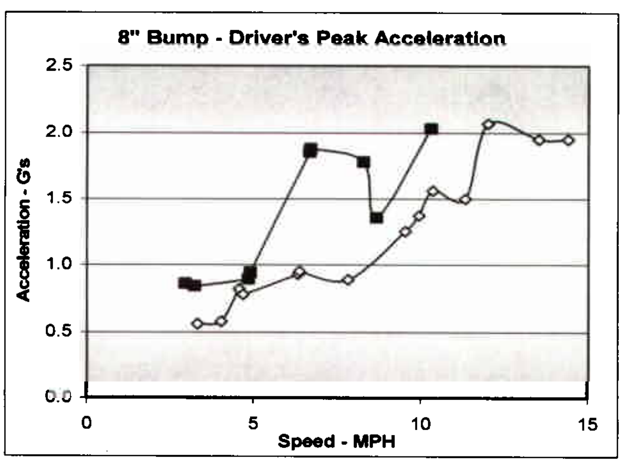

Figure 28 - 8" Bump Driver's Acceleration

The comparison of driver's peak acceleration over obstacles for the two test vehicles is summarized in Figure 29. This comparison, it should be noted, is made at the 1.5 G vertical acceleration level. This was done because the test data in 5 of the 6 cases shown never appreciably exceeded 2 Gs. The 1.5 G shock speed is improved by about 20% on the 4" bump, about 100% on the 6" bump, and by about 60% over the 8-inch obstacles.

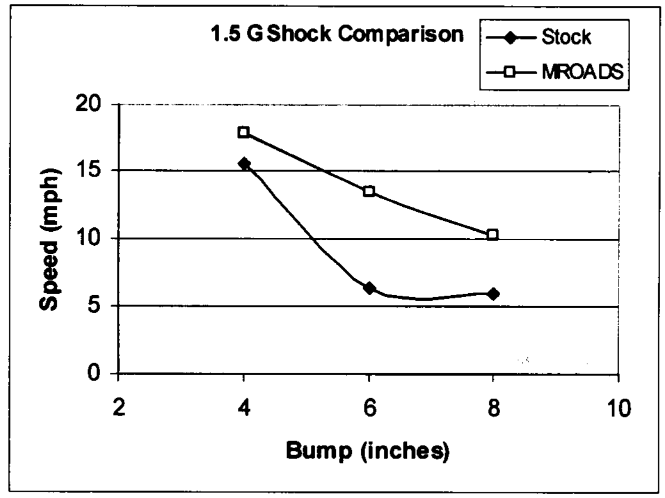

Figure 29 – 1.5 G Shock Comparison

Maneuverability Performance

The maneuverability of the MROADS Hummer and the passive HMMWV was compared based on slalom and lane change maneuvers as described earlier. Since these two tests exercise the vehicles in essentially the same manner, only the results of the lane change tests are reported here. The signals of interest for these tests were taken to be the suspension travel at each wheel, the chassis lateral acceleration, the chassis roll rate and roll angle, the chassis yaw rate, and the steering command angle. Further, since the lane change maneuver involves both a left and a right turn of approximately equal severity, only the suspension (or wheel) travel on the left side of the vehicle is considered. For most of these signals of interest, plots are included for the minimum and maximum signal levels experienced in each of the constant speed runs of the MROADS Hummer and the passive HMMWV. The wheel travel, however is reported as the total wheel travel used (as it was in the RMS course runs shown earlier), and the lateral acceleration is simply the largest magnitude of lateral acceleration experienced for each run.

Figures 30-31 record the total range of suspension travel used, as a function of vehicle speed for the Hummer and the HMMWV test vehicles. The wheel travel is consistently almost twice as great for the MROADS Hummer as it is for the stock HMMWV.

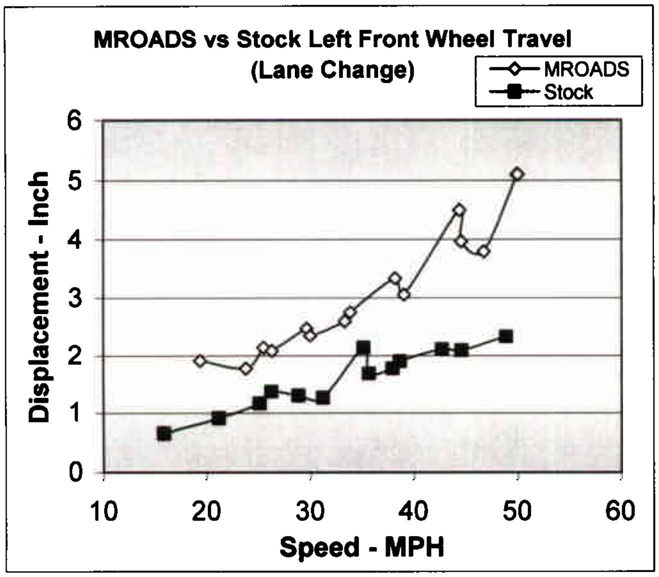

Figure 30 - Left Front Wheel Travel (Lane Change)

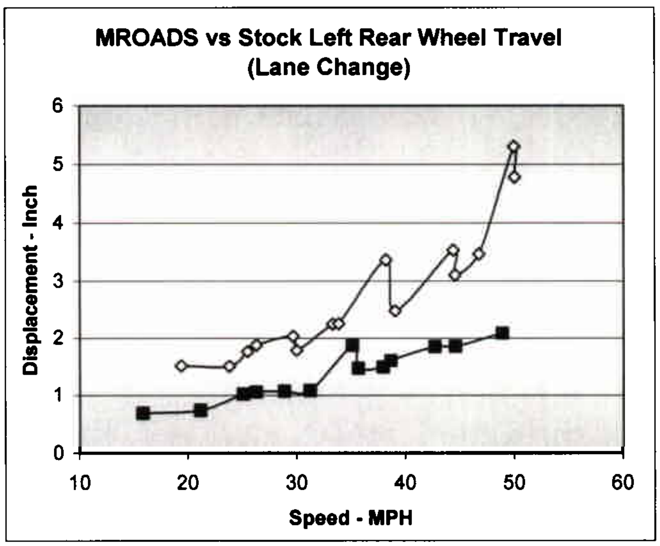

Figure 31 - Left Rear Wheel Travel (Lane Change)

This fact is not really reflected by the corresponding extremes of chassis roll angle and roll rate signals recorded in Figures 32-33. At the higher speeds (greater than 40 mph), the MROADS Hummer does demonstrate a somewhat higher negative roll angle in Figure 32, but overall the roll angles and rates of the two test vehicles are quite similar.

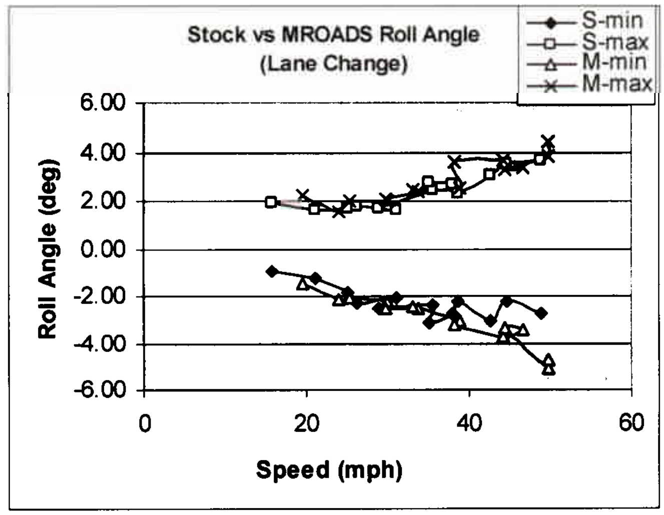

Figure 32 - Roll Angle (Lane Change)

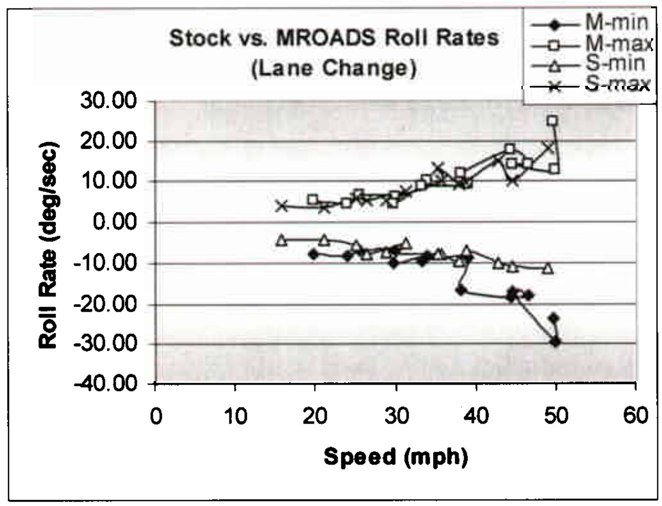

Figure 33 - Roll Rate (Lane Change)

Figures 34-35 record the minimum and maximum values for the steering command and the resulting vehicle yaw rate for each test run. It is not clear why the MROADS Hummer experienced significantly higher yaw rates than the stock HMMWV for all speeds on the lane change course. It is presumed that the two vehicles would do about the same amount of yawing during the total maneuver so this peak value may just reflect the vehicle's responsiveness to a steering input.

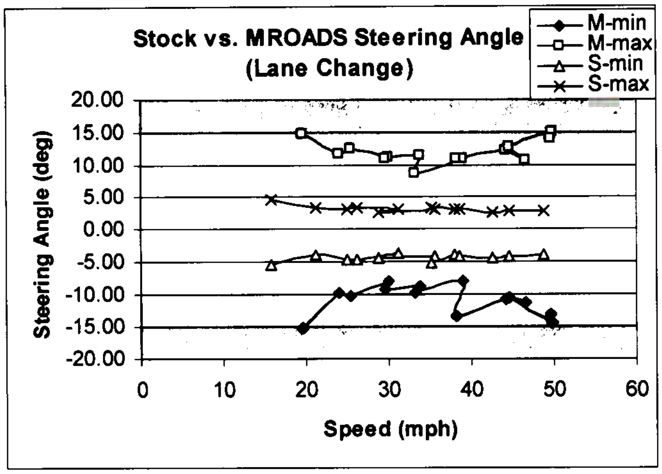

Figure 34 - Steering Angle (Lane Change)

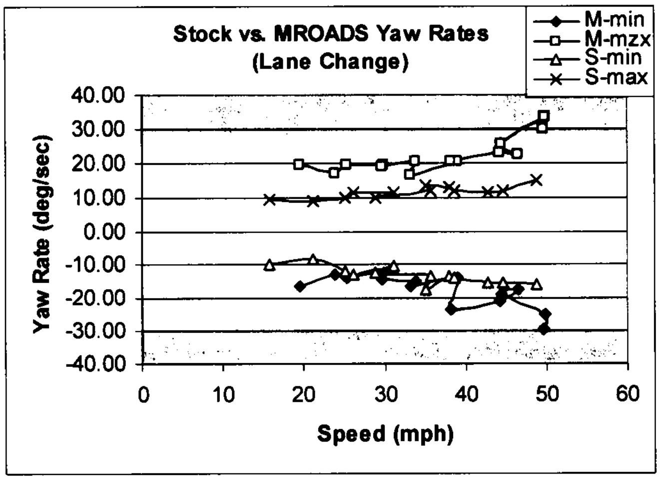

Figure 35 - Yaw Rate (Lane Change)

The lateral acceleration of the active and passive systems is shown in Figure 36. Once again the passive system has a somewhat better performance than does the active.

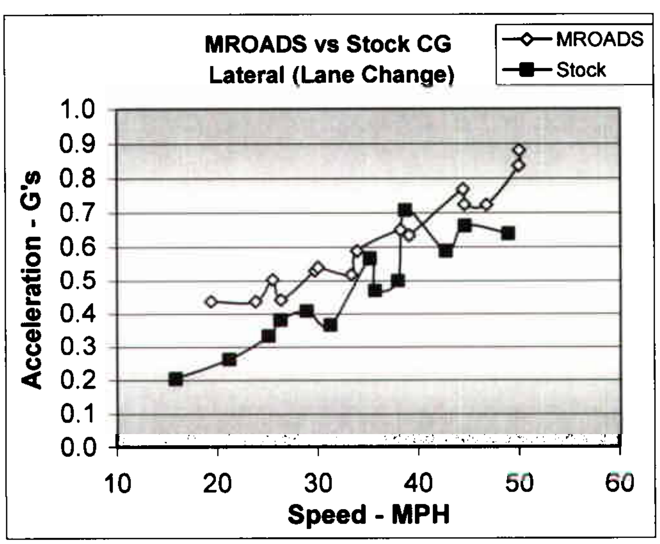

Figure 36 - CG Lateral Acceleration (Lane Change)

A couple of additional comments concerning the lane change performance tests are in order. The cg height of the stock M1037 HMMWV is rather low as HMMWV variants go. It is expected that the cg of the commercial Hummer is a bit higher. Also, as mentioned earlier, the rear suspension used on the MROADS Hummer is considerably softer than that on the stock HMMWV. Also any difference in height of the center of gravity between the two test vehicles affects their behavior in the lane change and slalom tests.

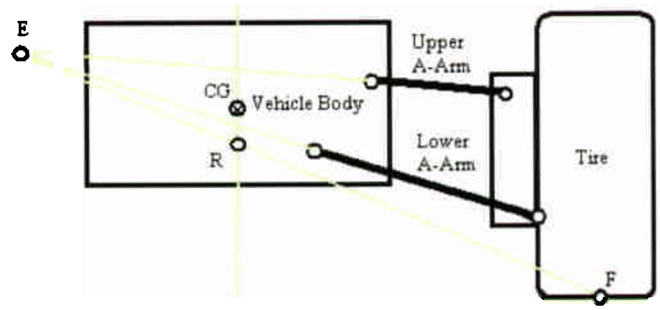

Figure 37 - Vehicle Roll Center

Lateral tire forces are applied to the sprung mass at the roll centers of the respective axles to produce a torque about the vehicle chassis' roll axis (through the sprung c.g.). The roll center for each axle is determined by the vehicle's suspension geometry and is defined as the point on the vehicle's longitudinal centerline at which the lateral axle forces are applied to the sprung mass. The average roll center height for the two axles of the HMMWV is 15.6 inches. Since the M1037 HMMWV has a listed curb c.g. height of 28.4", this gives a roll moment arm of 12.8 inches for the tire (or axle) lateral forces. This roll moment arm length is undoubtedly greater for the MROADS Hummer. The ratio of (MROADS moment arm) / 12.8 will multiply a given set of tire lateral forces (produced by turning) and result in increased torque about the roll axis in the Hummer than in the stock M1037 HMMWV.

RESULTS AND OBSERVATIONS

The ride quality performance of the MROADS Hummer with the semiactive MR fluid suspension was quite impressive. It is difficult to accurately attribute the amount of performance gain due only to the semiactive MR fluid dampers since the MROADS Hummer was also provided with a height control system and a significant increase in suspension travel.

The performance of the MROADS Hummer in the lane change maneuvers was less impressive and actually seemed slightly worse than that of the passive HMMWV. As noted earlier, this is probably at least partially due to different cg heights and possibly not having the system optimally tuned for lateral stability in the lane change maneuvers.

The difference in base vehicles certainly clouds the performance comparison process. The base suspensions were significantly different and the cg height and sprung mass inertias of the commercial Hummer were not available for comparison.

ACKNOWLEDGEMENTS

The authors would like to thank all of those involved, especially Instrumentation, Data Collection, Video, and the Drivers from YPG

CONTACT

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

cg - Center of Gravity
CFS – Compressible Fluid Suspension
CRADA – Cooperative Research and Development Agreement
EMS – Electromechanical Suspension
HMMWV - High Mobility Multi-purpose Wheeled Vehicle
MPH - Mile per hour
rms - Root Mean Square
TACOM - U.S. Army Tank-automotive and Armaments Command
TARDEC U.S. Army Tank-Automotive Research, Development and Engineering Center
YPG - Yuma Proving Grounds

APPENDIX A - Scope of Work

13August 02/Rod Millen Test at YUMA

1 SCOPE. This Scope of Work (SOW) covers technical support and testing services to be provided to the Mobility Directorate of the U.S. Army Tank-automotive and Armaments Command (TACOM). This support encompasses technical work and the use of test facilities.

1.1 Background. TACOM is involved in the development of advanced suspension technology to increase the mobility performance of Army vehicles. The particular application of a magneto-rheological fluid semi-active suspension (MR) to achieve increased performance is being explored. Comparison testing between the MR fluid suspension and a passive system is being sought to quantify the actual performance gains for ride quality, shock, and maneuverability. The platform for this particular test is the High Mobility Multi-purpose Wheeled Vehicle (HMMWV). One test period of one to two weeks is planned for running both the MR fluid suspension vehicle and the passive HMMWV.

2 APPLICABLE DOCUMENTS.

2.1 Course Layouts. See Appendix A1.

2.2 Testing Procedures. See Appendix A2.

3 REQUIRMENTS.

3.1 General. Use of the test facilities shall include support of test personnel, preparation of test areas or courses in conjunction with tests requested, installation of data collection equipment and instrumentation, and production of test results in digital form on CD-ROM or Zip disk format and video requested. TACOM will coordinate the overall test program with cooperation from Rod Millen Special Vehicles, and arrange delivery of the MR Hummer. Testing shall begin upon the arrival of the MR Hummer. All test results shall be delivered no later than 30 days after final testing is completed.

3.2 Instrumentation. The passive HMMWV vehicle shall be instrumented with sensors mounted on solid non-resonating surfaces to measure the following at the specified location:

3.2.1.1 Vertical acceleration on vehicle body above each wheel (4 sensors)

3.2.1.2 Vertical acceleration on each wheel near knuckle assembly (4 sensors)

3.2.1.3 Differential position of suspension or wheel travel for each wheel (4 sensors)

3.2.1.4 Tri-axial acceleration at CG (vertical, longitudinal, lateral) (1 sensor)

3.2.1.5 Tri-axial angular rate at CG (roll, pitch, yaw) (1 sensor)

3.2.1.6 Speed (longitudinal) (1 sensor)

3.2.1.7 Steering angle (1 sensor)

3.2.1.8 Vertical acceleration at driver's floor (1 sensor)

3.2.2 An Instrumentation Map shall be provided for each test conducted.

3.3 Test Descriptions.

3.3.1 Ride. Ride quality tests shall be conducted according to the test procedure described in the Appendix (A2). Each vehicle shall be driven over the following courses (approx. RMS) starting at 5 MPH in 5-MPH increments (refinement to 2.5-MPH increments may be needed for special cases):

3.3.1a Rolling Resistance. The Rolling Resistance or "Coast Down" test should be conducted on the MR Hummer and passive HMMWV. Tests should be conducted on level, Course 3 (1.5" RMS), and Course 4 (2.0" RMS) from a range starting at 15 MPH and ending at 25 MPH.:

3.3.1.1 Course 2 - 1.3" RMS roughness

3.3.1.2 Course 3 - 1.5" RMS roughness

3.3.1.3 Course 4 - 2.0" RMS roughness

3.3.1.4 Course 5 - 3.4" RMS roughness

3.3.2 Shock. Shock level tests shall be conducted according to the test procedure described in the Appendix (A2). Each vehicle shall be driven over the following, full vehicle width, half-round bump heights starting at 5 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases):

3.3.2.0 4" half-round

3.3.2.1 6" half-round

3.3.2.2 8" half-round

3.3.2.3 10" half-round

3.3.2.4 12" half-round

3.3.3 Maneuverability.

3.3.3.1 Double Lane Change. Double Lane Change tests shall be conducted according to the test procedure described in the Appendix (A2). (For the case of the HMMWV the vehicle length and width shall be 15 ft and 7 ft, respectively). Each vehicle shall be driven over the course starting at 40 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases).

3.3.3.2 Constant Step Slalom. Constant Step Slalom tests shall be conducted according to the test procedure described in the Appendix (A2). Each vehicle shall be driven over the course with the following cone spacing starting at 5 MPH in 5-MPH increments (refinement to 2.5 MPH increments may be needed for special cases):

3.3.3.2.1 d = 10 m (32.8 ft)
3.3.3.2.2 d = 15 m (49.2 ft)
3.3.3.2.3 d = 20 m (65.6 ft)
3.3.3.2.4 d = 30 m (98.4 ft)

3.4 Data Acquisition. All tests shall be run at constant speeds, each run incrementally increasing to reaching the ride limiting speed or until deemed unsafe. A check of test data shall be made after each run and if any channel failure or dropout is present that test shall be rerun in entirety. The sample rate will be conducted at 500 Hz and all channel data for each test shall be stored and delivered on CD-ROM or Zip Disk format media in ASCII format (including file content description). Side and frontal video shots shall be taken of each test. A digital profile of all ride courses used shall be provided.

APPENDIX

A1 COURSE LAYOUTS

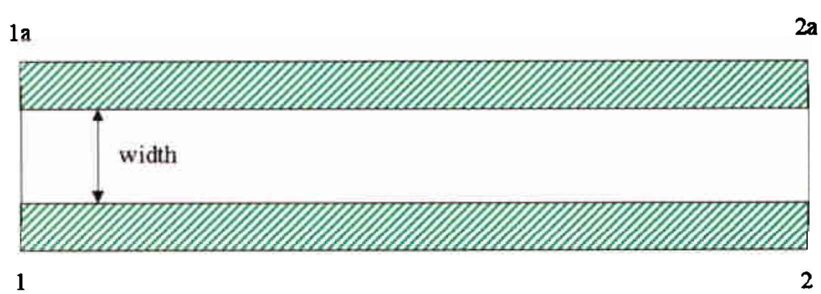

Figure A1 - Ride Course Layout

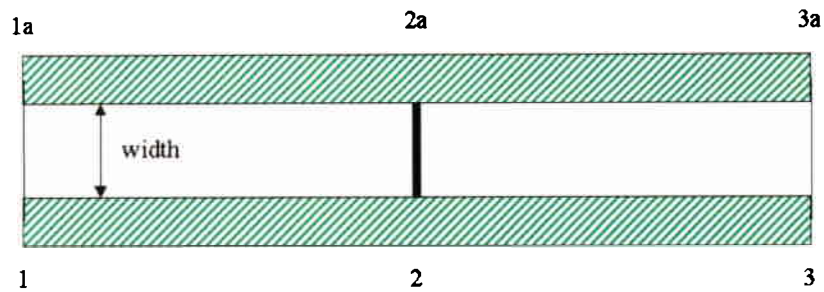

Figure A2 - Bump Course Layout

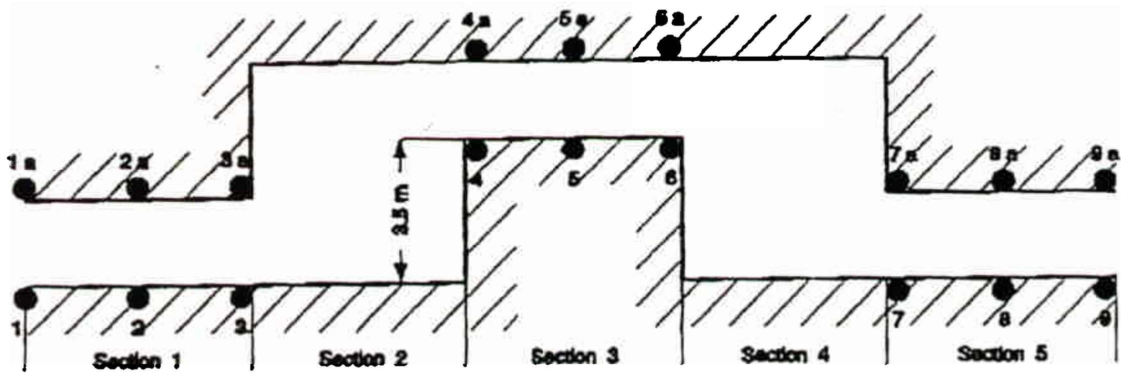

Figure A3 - Lane Change Layout

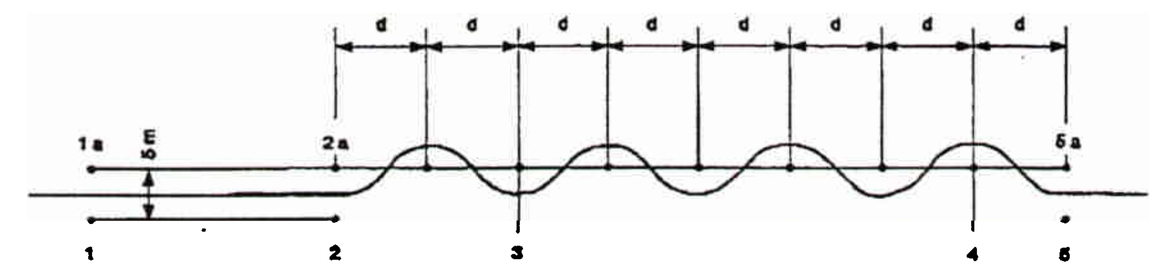

Figure A4 - Constant Step Slalom Layout

A2 TEST PROCEDURES

A2.1 Ride.

A2.1.a Set up the course shown (Figure A1) with width at least two times the vehicle width and with distance (1-2) at least 150 m (492 ft).

A2.1.b Cross the line (1-1a) at the lowest vehicle speed laid down in the test plan and drive in a straight line through the section (1-2); attempt to continue through the remainder of the course whilst keeping the speed as steady as possible at this same value. Record parameters and note the vehicle behavior during the test.

A2.1.c Repeat (b) at the various speed increments laid down in test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without staying on the course or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A2.1.d Repeat the above procedure (a) to (c), but with the courses roughness as laid down in the test plan.

A2.2 Shock.

A2.2.a Set up the course shown (Figure A2) with width at least two times the vehicle width including a full vehicle width half-round bump at (2-2a).

A2.2.b Cross the line (1-1a) at the lowest vehicle speed laid down in the test plan and drive in a straight line through the section (1-3); attempt to continue through the remainder of the course whilst keeping the speed as steady as possible at this same value. Record parameters and note the vehicle behavior during the test.

A2.2.c Repeat (b) at the various speed increments laid down in test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without staying on the course or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A2.2.d Repeat the above procedure (a) to (c), but with the half-round bump height as laid down in the test plan.

A3.3 Maneuverability.

A3.3.1 Double Lane Change.

A3.3.1.a Set up the course shown (Figure A3) with the following dimensions:

Section 1: Length = 15 m (49.2 ft)
Width = 1.1 * vehicle width + 0.25 m (0.82 ft)

Section 2: Length = vehicle length + 24 m (78.72 ft)
Width = 3.5 m (11.48 ft) + Section 3 width

Section 3: Length = 25 m (82 ft)
Width = 1.2 * vehicle width + 0.25m (0.82 ft)

Section 4: Length = vehicle length + 24 m (78.72 ft)
Width = 3.5 m (11.48 ft) + Section 3 width

Section 5: Length = 15 m (49.2 ft)
Width = 1.1 * vehicle width + 0.25 m (0.82 ft)

A3.3.1.b Cross the line (1-1a) with the lowest vehicle speed laid down in test plan and drive in a straight line through the first section (1-3); attempt to continue through the remainder of the course (3-9) whilst keeping the speed as steady as possible at this same value. Record parameters and note the vehicle behavior during the test.

A3.3.1.c Repeat (b) at the various speed increments laid down in the test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without knocking the cones down or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A3.3.2 Constant Step Slalom.

A3.3.2.a Set up the course shown (Figure A4) with distance "d" as laid out in the test plan and with distances (1-1a, 2-2a, 5-5a) at 5 m (16.4 ft).

A3.3.2.b Cross the line (1-1a) at the lowest vehicle speed laid down in the test plan and drive in a straight line through the section (1-2); attempt to continue through the remainder of the course (2-5)) whilst keeping the speed as steady as possible at this same value. The time needed to cross the section (3-4) is to be measured. Record parameters and note the vehicle behavior during the test.

A3.3.2.c Repeat (b) at the various speed increments laid down in test plan until: 1) maximum speed laid down in the test plan is reached or 2) it becomes impossible to cross the test area without knocking the cones down or 3) a speed is reached at which there is a risk of the vehicle falling onto its side, whichever occurs first.

A3.3.2.d Repeat the above procedure (a) to (c), but with the distances "d" set in turn at 15, 20 and 30 m (49.2, 65.6, and 98.4 ft).

APPENDIX B - Test Matrix

MR FLUID HMMWV SUSPENSION TEST
7-9 JANUARY 2003

Run	Direction	Speed	Scenario	Vehicle	Driver
1	N	10	RMS Course 3	Active	Buzzard
2	N	5	RMS Course 3	Passive	Jerry
3	S	5	RMS Course 3	Passive	Jerry
4	S	10	RMS Course 3	Active	Buzzard
5	N	20	RMS Course 3	Active	Buzzard
6	N	10	RMS Course 3	Passive	Jerry
7	S	10	RMS Course 3	Passive	Jerry
8	S	20	RMS Course 3	Active	Buzzard
9	N	15	RMS Course 3	Passive	Jerry
10	S	15	RMS Course 3	Passive	Jerry
11	N	25	RMS Course 3	Active	Buzzard
12	S	25	RMS Course 3	Active	Buzzard
13	N	30	RMS Course 3	Active	Buzzard
14	S	30	RMS Course 3	Active	Buzzard
15	N	10	RMS Course 3	Passive	Jerry
16	S	10	RMS Course 3	Passive	Jerry
17	N	35	RMS Course 3	Active	Buzzard
18	S	35	RMS Course 3	Active	Buzzard
19	N	40	RMS Course 3	Active	Buzzard
20	S	40	RMS Course 3	Active	Buzzard
21	N	45	RMS Course 3	Active	Buzzard
22	N	20	RMS Course 3	Passive	Jerry
23	S	20	RMS Course 3	Passive	Jerry
24	N	25	RMS Course 3	Passive	Jerry
25	S	25	RMS Course 3	Passive	Jerry
26	S	45	RMS Course 3	Active	Buzzard
27	N	50	RMS Course 3	Active	Buzzard
28	S	50	RMS Course 3	Active	Buzzard
29	N	15	RMS Course 3	Active	Buzzard
30	N	30	RMS Course 3	Passive	Jerry
31	S	30	RMS Course 3	Passive	Jerry
32	N	35	RMS Course 3	Passive	Jerry
33	S	35	RMS Course 3	Passive	Jerry
34	S	15	RMS Course 3	Active	Buzzard
35	N	40	RMS Course 3	Passive	Jerry
36	S	50	RMS Course 3	Active	Buzzard
37	S	40	RMS Course 3	Passive	Jerry
38	N	45	RMS Course 3	Passive	Jerry
39	S	45	RMS Course 3	Passive	Jerry
1	N	15	RMS 3 - RolRes	Passive	Jerry
2	N	20	RMS 3 - RolRes	Passive	Jerry
3	N	25	RMS 3 - RolRes	Passive	Jerry
4	N	30	RMS 3 - RolRes	Passive	Jerry
5	N	15	RMS 3 - RolRes	Active	Buzzard

Run	Direction	Speed	Scenario	Vehicle	Driver
6	N	20	RMS 3 - RolRes	Active	Buzzard
7	N	25	RMS 3 - RolRes	Active	Buzzard
8	N	30	RMS 3 - RolRes	Active	Buzzard
1	N	5	RMS Course 4	Active	Buzzard
2	N	5	RMS Course 4	Passive	Jerry
3	S	5	RMS Course 4	Passive	Jerry
4	N	10	RMS Course 4	Passive	Jerry
5	S	10	RMS Course 4	Passive	Jerry
6	S	5	RMS Course 4	Active	Buzzard
7	N	15	RMS Course 4	Passive	Jerry
8	S	15	RMS Course 4	Passive	Jerry
9	N	10	RMS Course 4	Active	Buzzard
10	N	20	RMS Course 4	Passive	Jerry
11	S	20	RMS Course 4	Passive	Jerry
12	N	25	RMS Course 4	Passive	Jerry
13	S	25	RMS Course 4	Passive	Jerry
14	S	10	RMS Course 4	Active	Buzzard
15	N	30	RMS Course 4	Passive	Jerry
16	S	30	RMS Course 4	Passive	Jerry
17	N	15	RMS Course 4	Active	Buzzard
18	S	15	RMS Course 4	Active	Buzzard
19	N	20	RMS Course 4	Active	Buzzard
20	S	20	RMS Course 4	Active	Buzzard
21	N	25	RMS Course 4	Active	Buzzard
22	S	25	RMS Course 4	Active	Buzzard
23	N	30	RMS Course 4	Active	Buzzard
24	S	30	RMS Course 4	Active	Buzzard
25	N	35	RMS Course 4	Active	Buzzard
1	N	15	RMS 4 - RolRes	Passive	Jerry
2	N	20	RMS 4 - RolRes	Passive	Jerry
3	N	25	RMS 4 - RolRes	Passive	Jerry
4	N	30	RMS 4 - RolRes	Passive	Jerry
5	N	15	RMS 4 - RolRes	Active	Buzzard
6	N	20	RMS 4 - RolRes	Active	Buzzard
7	N	25	RMS 4 - RolRes	Active	Buzzard
8	N	30	RMS 4 - RolRes	Active	Buzzard
1	N	5	RMS Course 5	Passive	Jerry
2	S	5	RMS Course 5	Passive	Jerry
3	N	5	RMS Course 5	Active	Buzzard
4	N	10	RMS Course 5	Passive	Jerry
5	S	10	RMS Course 5	Passive	Jerry
6	N	15	RMS Course 5	Passive	Jerry
7	S	5	RMS Course 5	Active	Buzzard
8	N	10	RMS Course 5	Active	Buzzard
9	S	10	RMS Course 5	Active	Buzzard
10	N	15	RMS Course 5	Active	Buzzard
11	S	15	RMS Course 5	Active	Buzzard
1	N	10	RMS 5 - RolRes	Passive	Jerry
2	N	15	RMS 5 - RolRes	Passive	Jerry
3	N	10	RMS 5 - RolRes	Active	Buzzard

Run	Direction	Speed	Scenario	Vehicle	Driver
4	N	15	RMS 5 - RolRes	Active	Buzzard
1	S	5	Slolam - 10m	Active	Buzzard
2	N	5	Slolam - 10m	Active	Buzzard
3	N	5	Slolam - 10m	Passive	Jerry
4	S	5	Slolam - 10m	Passive	Jerry
5	S	7.5	Slolam - 10m	Active	Buzzard
6	N	7.5	Slolam - 10m	Passive	Jerry
7	N	10	Slolam - 10m	Active	Buzzard
8	N	10	Slolam - 10m	Passive	Jerry
9	S	10	Slolam - 10m	Passive	Jerry
10	N	12.5	Slolam - 10m	Passive	Jerry
11	S	12.5	Slolam - 10m	Active	Buzzard
12	N	15	Slolam - 10m	Active	Buzzard
13	S	15	Slolam - 10m	Active	Buzzard
1	N	10	Slolam - 15m	Active	Buzzard
2	N	10	Slolam - 15m	Passive	Jerry
3	S	10	Slolam - 15m	Passive	Jerry
4	S	10	Slolam - 15m	Active	Buzzard
5	N	15	Slolam - 15m	Passive	Jerry
6	S	15	Slolam - 15m	Passive	Jerry
7	N	20	Slolam - 15m	Passive	Jerry
8	S	20	Slolam - 15m	Passive	Jerry
9	N	15	Slolam - 15m	Active	Buzzard
10	N	25	Slolam - 15m	Passive	Jerry
11	S	15	Slolam - 15m	Active	Buzzard
12	S	22.5	Slolam - 15m	Passive	Jerry
13	N	22.5	Slolam - 15m	Passive	Jerry
14	N	20	Slolam - 15m	Active	Buzzard
15	S	20	Slolam - 15m	Active	Buzzard
16	N	25	Slolam - 15m	Active	Buzzard
17	S	25	Slolam - 15m	Active	Buzzard
18	N	27.5	Slolam - 15m	Active	Buzzard
1	N	10	Slolam - 20m	Passive	Jerry
2	N	10	Slolam - 20m	Active	Buzzard
3	S	15	Slolam - 20m	Active	Buzzard
4	S	15	Slolam - 20m	Passive	Jerry
5	N	20	Slolam - 20m	Passive	Jerry
6	N	20	Slolam - 20m	Active	Buzzard
7	S	20	Slolam - 20m	Passive	Jerry
8	S	20	Slolam - 20m	Active	Buzzard
9	N	25	Slolam - 20m	Passive	Jerry
10	S	25	Slolam - 20m	Passive	Jerry
11	N	25	Slolam - 20m	Active	Buzzard
12	N	30	Slolam - 20m	Passive	Jerry
13	S	25	Slolam - 20m	Active	Buzzard
14	S	30	Slolam - 20m	Passive	Jerry
15	N	30	Slolam - 20m	Active	Buzzard
16	S	30	Slolam - 20m	Active	Buzzard

Run	Direction	Speed	Scenario	Vehicle	Driver
1	N	15	Slolam - 30m	Active	Buzzard
2	N	15	Slolam - 30m	Passive	Jerry
3	S	20	Slolam - 30m	Passive	Jerry
4	S	20	Slolam - 30m	Active	Buzzard
5	N	25	Slolam - 30m	Passive	Jerry
6	S	25	Slolam - 30m	Passive	Jerry
7	N	25	Slolam - 30m	Active	Buzzard
8	N	30	Slolam - 30m	Passive	Jerry
9	S	30	Slolam - 30m	Passive	Jerry
10	S	25	Slolam - 30m	Active	Buzzard
11	N	35	Slolam - 30m	Passive	Jerry
12	S	35	Slolam - 30m	Passive	Jerry
13	N	30	Slolam - 30m	Active	Buzzard
14	N	40	Slolam - 30m	Passive	Jerry
15	S	30	Slolam - 30m	Active	Buzzard
16	S	40	Slolam - 30m	Passive	Jerry
17	N	45	Slolam - 30m	Passive	Jerry
18	N	35	Slolam - 30m	Active	Buzzard
19	S	42.5	Slolam - 30m	Passive	Jerry
20	S	35	Slolam - 30m	Active	Buzzard
21	N	40	Slolam - 30m	Active	Buzzard
22	S	40	Slolam - 30m	Active	Buzzard
23	N	45	Slolam - 30m	Active	Buzzard
24	S	45	Slolam - 30m	Active	Buzzard
25	N	40	Slolam - 30m	Active	Buzzard
26	S	40	Slolam - 30m	Active	Buzzard
1	N	15	Lane Change	Active	Buzzard
2	N	15	Lane Change	Passive	Jerry
3	S	20	Lane Change	Passive	Jerry
4	S	20	Lane Change	Active	Buzzard
5	N	25	Lane Change	Passive	Jerry
6	S	25	Lane Change	Passive	Jerry
7	N	25	Lane Change	Active	Buzzard
8	N	30	Lane Change	Passive	Jerry
9	S	30	Lane Change	Passive	Jerry
10	S	25	Lane Change	Active	Buzzard
11	N	35	Lane Change	Passive	Jerry
12	S	35	Lane Change	Passive	Jerry
13	N	30	Lane Change	Active	Buzzard
14	N	40	Lane Change	Passive	Jerry
15	S	30	Lane Change	Active	Buzzard
16	S	40	Lane Change	Passive	Jerry
17	N	35	Lane Change	Active	Buzzard
18	N	45	Lane Change	Passive	Jerry
19	S	35	Lane Change	Active	Buzzard
20	S	45	Lane Change	Passive	Jerry
21	N	40	Lane Change	Active	Buzzard
22	N	50	Lane Change	Passive	Jerry
23	S	40	Lane Change	Active	Buzzard

Run	Direction	Speed	Scenario	Vehicle	Driver
1	N	3	4inchBumps	Passive	Jerry
2	S	3	4inchBumps	Passive	Jerry
3	N	5	4inchBumps	Passive	Jerry
4	S	5	4inchBumps	Passive	Jerry
5	N	7	4inchBumps	Passive	Jerry
6	S	7	4inchBumps	Passive	Jerry
7	N	9	4inchBumps	Passive	Jerry
8	S	9	4inchBumps	Passive	Jerry
9	N	11	4inchBumps	Passive	Jerry
10	S	11	4inchBumps	Passive	Jerry
11	N	13	4inchBumps	Passive	Jerry
12	S	13	4inchBumps	Passive	Jerry
13	N	15	4inchBumps	Passive	Jerry
14	S	15	4inchBumps	Passive	Jerry
15	N	17	4inchBumps	Passive	Jerry
16	S	17	4inchBumps	Passive	Jerry
17	N	20	4inchBumps	Passive	Jerry
18	S	20	4inchBumps	Passive	Jerry
1	N	3	4inchBumps	Active	Buzzard
2	S	5	4inchBumps	Active	Buzzard
3	N	7	4inchBumps	Active	Buzzard
4	S	9	4inchBumps	Active	Buzzard
5	N	11	4inchBumps	Active	Buzzard
6	S	11	4inchBumps	Active	Buzzard
7	N	13	4inchBumps	Active	Buzzard
8	S	13	4inchBumps	Active	Buzzard
9	N	15	4inchBumps	Active	Buzzard
10	S	15	4inchBumps	Active	Buzzard
11	N	17	4inchBumps	Active	Buzzard
12	S	17	4inchBumps	Active	Buzzard
13	N	20	4inchBumps	Active	Buzzard
14	S	20	4inchBumps	Active	Buzzard
15	N	25	4inchBumps	Active	Buzzard
16	S	25	4inchBumps	Active	Buzzard
1	N	3	6inchBumps	Passive	Jerry
2	S	3	6inchBumps	Passive	Jerry
3	N	5	6inchBumps	Passive	Jerry
4	S	5	6inchBumps	Passive	Jerry
5	N	7	6inchBumps	Passive	Jerry
6	S	7	6inchBumps	Passive	Jerry
7	N	9	6inchBumps	Passive	Jerry
8	S	9	6inchBumps	Passive	Jerry
9	N	11	6inchBumps	Passive	Jerry
10	S	11	6inchBumps	Passive	Jerry
11	N	13	6inchBumps	Passive	Jerry
12	S	13	6inchBumps	Passive	Jerry
13	N	15	6inchBumps	Passive	Jerry
14	S	15	6inchBumps	Passive	Jerry

Run	Direction	Speed	Scenario	Vehicle	Driver
15	N	17	6inchBumps	Passive	Jerry
1	N	3	6inchBumps	Active	Buzzard
2	S	3	6inchBumps	Active	Buzzard
3	N	5	6inchBumps	Active	Buzzard
4	S	5	6inchBumps	Active	Buzzard
5	N	7	6inchBumps	Active	Buzzard
6	S	7	6inchBumps	Active	Buzzard
7	N	9	6inchBumps	Active	Buzzard
8	S	9	6inchBumps	Active	Buzzard
9	N	11	6inchBumps	Active	Buzzard
10	S	11	6inchBumps	Active	Buzzard
11	N	13	6inchBumps	Active	Buzzard
12	S	13	6inchBumps	Active	Buzzard
13	N	15	6inchBumps	Active	Buzzard
14	S	15	6inchBumps	Active	Buzzard
15	N	17	6inchBumps	Active	Buzzard
16	S	17	6inchBumps	Active	Buzzard
17	N	20	6inchBumps	Active	Buzzard
18	S	20	6inchBumps	Active	Buzzard
1	N	3	8inchBumps	Passive	Jerry
2	S	3	8inchBumps	Passive	Jerry
3	N	5	8inchBumps	Passive	Jerry
4	S	5	8inchBumps	Passive	Jerry
5	N	7	8inchBumps	Passive	Jerry
6	S	7	8inchBumps	Passive	Jerry
7	N	9	8inchBumps	Passive	Jerry
8	S	9	8inchBumps	Passive	Jerry
9	N	11	8inchBumps	Passive	Jerry
1	N	3	8inchBumps	Active	Buzzard
2	S	3	8inchBumps	Active	Buzzard
3	N	5	8inchBumps	Active	Buzzard
4	S	5	8inchBumps	Active	Buzzard
5	N	7	8inchBumps	Active	Buzzard
6	S	7	8inchBumps	Active	Buzzard
7	N	9	8inchBumps	Active	Buzzard
8	S	9	8inchBumps	Active	Buzzard
9	N	11	8inchBumps	Active	Buzzard
10	S	11	8inchBumps	Active	Buzzard
11	N	13	8inchBumps	Active	Buzzard
12	S	13	8inchBumps	Active	Buzzard
13	N	15	8inchBumps	Active	Buzzard
14	S	15	8inchBumps	Active	Buzzard

APPENDIX C - Passive HMMWV Sensor Instrumentation List

Passive HMMWV Sensor List

Channel #	Sensor	Location	Type	Elements	Direction	Scale Factor	Coordinates (in)	Comments
1	Wheel Acceleration Vertical axis "Gs"	Right Front Hub	Capacitance Accelerometer	1	Up = Positive	.		
2	Wheel Acceleration Vertical axis "Gs"	Left Front Hub	Capacitance Accelerometer	1	Up = Positive	.		
3	Wheel Acceleration Vertical axis "Gs"	Right Rear Hub	Capacitance Accelerometer	1	Up = Positive	.		
4	Wheel Acceleration Vertical axis "Gs"	Left Rear Hub	Capacitance Accelerometer	1	Up = Positive	.		
5	Frame Acceleration Vertical axis "Gs"	Right Front Frame	Capacitance Accelerometer	1	Up = Positive			
6	Frame Acceleration Vertical axis "Gs"	Left Front Frame	Capacitance Accelerometer	1	Up = Positive			
7	Frame Acceleration Vertical axis "Gs"	Right Rear Frame	Capacitance Accelerometer	1	Up = Positive			
8	Frame Acceleration Vertical axis "Gs"	Left Rear Frame	Capacitance Accelerometer	1	Up = Positive			
9	CG Longitudinal Acceleration X axis "Gs"	Cargo area sheetmetal between seats	Capacitance Accelerometer	1	Forward = Positive	.		Endevco 7290A-30, ± 30g, 0-800 Hz
10	CG Lateral Acceleration Y axis "Gs"	Cargo area sheetmetal between seats	Capacitance Accelerometer	1	Left = Positive	.		Endevco 7290A-30, ± 30g, 0-800 Hz

Channel #	Sensor	Location	Type	Elements	Direction	Scale Factor	Coordinates (in)	Comments
11	CG Vertical Acceleration Z axis "Gs"	Cargo area sheetmetal between seats	Capacitance Accelerometer	1	Up = Positive	.		Endevco 7290A-30 ± 30g, 0-800 Hz
12	Driver's Vertical Acceleration "Gs"	Frame crossmember behind seat	Capacitance Accelerometer	1	Up = Positive	.		Endevco 7290A-10 ± 10g
13	Pitch "Deg/sec"	Cargo area Sheetmetal between seats	3-Axis Rate Transducer	1	Nose Down= Positive	.		
14	Roll "Deg/sec"	Cargo area Sheetmetal between seats	3-Axis Rate Transducer	1	Roll Left= Positive	.		
15	Yaw "Deg/sec"	Cargo area Sheetmetal between seats	3-Axis Rate Transducer	1	Nose Right= Positive	.		
16	Road Speed "MPH"	LR Wheel	Di-mag Pulse Counter	1	N/A			
17	Steering Angle "Degrees"	Frame crossmember behind seat	Linear Position Transducer	1	Right turn =Positive		Steering Gear Box Pitman Arm	Space Age Controls Inc. 160-1705 Position Transducer
18	Wheel Displacement LF "Inches"	Left Front Upper A-arm Ball Joint	Linear Position Transducer	1	Extension =Positive			UniMeasure PA-30-NJC 30 in
19	Wheel Displacement LR "Inches"	Left Rear Upper A-arm Ball Joint	Linear Position Transducer	1	Extension =Positive			UniMeasure PA-30-NJC 30 in
20	Wheel Displacement RF "Inches"	Right Front Upper A-arm Ball Joint	Linear Position Transducer	1	Extension =Positive			UniMeasure PA-30-NJC 30 in
21	Wheel Displacement RR "Inches"	Right Rear Upper A-arm Ball Joint	Linear Position Transducer	1	Extension = Positive			UniMeasure PA-30-NJC 30 in.

APPENDIX D - Test Hummer Sensor Instrumentation List

Analog Inputs

Input #	A-to-D Channel	A-to-D J3 pin #	Card	Type	Sensor	Vsupply, sensor	Sample Rate (Hz)	Lowpass filter freq.	Sensor Type
1	0	3	0	Single-ended	Brake Pressure	10-24V	500	50Hz	4-20mA
2	1	5	0	Single-ended	RF Load Lev. Pressure	10-24V	500	200Hz	4-20mA
3	2	7	0	Single-ended	LF Load Lev. Pressure	10-24V	500	200Hz	4-20mA
4	3	9	0	Single-ended	RR Load Lev. Pressure	10-24V	500	200Hz	4-20mA
5	4	11	0	Single-ended	LR Load Lev. Pressure	10-24V	500	200Hz	4-20mA
6	5	13	0	Single-ended	RF Shock Temp	N/A	500	25Hz	J-type T/C
7	6	15	0	Single-ended	LF Shock Temp	N/A	500	25Hz	J-type T/C
8	7	17	0	Single-ended	RR Shock Temp	N/A	500	25Hz	J-type T/C
9	8	19	0	Single-ended	LR Shock Temp	N/A	500	25Hz	J-type T/C
10	9	21	0	Single-ended	Steering Position	5V	500	50Hz	Pot
11	10	23	0	Single-ended	Throttle Position	5V	500	50Hz	Pot
12	11	25	0	Single-ended	Driver's Seat Accelerometer	12-15V	500		Accel
13	12	27	0	Single-ended					
14	13	29	0	Single-ended					
15	14	31	0	Single-ended					
16	15	33	0	Single-ended	RF Damper Force	N/A	500		Full Bridge
17	16	4	0	Single-ended	LF Damper Force	N/A	500		Full Bridge
18	17	6	0	Single-ended	RR Damper Force	N/A	500		Full Bridge
19	18	8	0	Single-ended	LR Damper Force	N/A	500		Full Bridge
20	19	10	0	Single-ended	Speed Sense	10-30V	500		
21	20	12	0	Single-ended					
22	21	14	0	Single-ended					
23	22	16	0	Single-ended					

Input #	A-to-D Channel	A-to-D J3 pin #	Card	Type	Sensor	Vsupply, sensor	Sample Rate (Hz)	Lowpass filter freq.	Sensor Type
24	23	18	0	Single-ended	Trans Amp FB (future option)				
25	0	3,4	1	Differential	RF Body Accelerometer	12-15V	2000		Accel
26	1	5,6	1	Differential	LF Body Accelerometer	12-15V	2000		Accel
27	2	7,8	1	Differential	RR Body Accelerometer	12-15V	2000		Accel
28	3	9,10	1	Differential	LR Body Accelerometer	12-15V	2000		Accel
29	4	11,12	1	Differential	RF Upright Accelerometer	12-15V	2000		Accel
30	5	13,14	1	Differential	LF Upright Accelerometer	12-15V	2000		Accel
31	6	15,16	1	Differential	RR Upright Accelerometer	12-15V	2000		Accel
32	7	17,18	1	Differential	LR Upright Accelerometer	12-15V	2000		Accel
33	8	19,20	1	Differential	Driver's Floor Accelerometer	12-15V	2000		Accel
34	9	21,22	1	Differential	RF Sus. Position	5V	2000	800Hz	Pot
35	10	23,24	1	Differential	LF Sus. Position	5V	2000	800Hz	Pot
36	11	25,26	1	Differential	RR Sus. Position	5V	2000	800Hz	Pot
37	12	27,28	1	Differential	LR Sus. Position	5V	2000	800Hz	Pot
38	13	29,30	1	Differential	Accel. X @ apprx C.G.	10-36V	2000		Triax @ CG
39	14	31,32	1	Differential	Accel. Y @ apprx C.G.	10-36V	2000		Triax @ CG
40	15	33,34	1	Differential	Accel. Z @ apprx C.G.	10-36V	2000		Triax @ CG

Analog Inputs

Input #	Notes: Filtering	Notes	Sensor
1	1 pole Butterworth		Ashcroft ASH-K1-5-MEK-42_H3-2000
2	1 pole Butterworth		Ashcroft ASH-K1-5-MEK-42_H3-2000
3	1 pole Butterworth		Ashcroft ASH-K1-5-MEK-42_H3-2000
4	1 pole Butterworth		Ashcroft ASH-K1-5-MEK-42_H3-2000
5	1 pole Butterworth		Ashcroft ASH-K1-5-MEK-42_H3-2000
6	1 pole Butterworth		Omega 5TC-TT-J-30_36
7	1 pole Butterworth		Omega 5TC-TT-J-30_36
8	1 pole Butterworth		Omega 5TC-TT-J-30_36
9	1 pole Butterworth		Omega 5TC-TT-J-30_36
10	5th order Bessel Filter	Use differential amp before filter	novotechnik SP 2831A502 ART. NR. 001921
11	5th order Bessel Filter	Use differential amp before filter	novotechnik SP 2831A502 ART. NR. 001921
12	5g sensor limited to 300Hz	Use differential amp	
13			
14			
15			
16	External signal conditioning		
17	External signal conditioning		
18	External signal conditioning		
19	External signal conditioning		
20		75.5 MPH = 250Hz(F-to-V Converter)	
21			
22			
23			
24		trans amp condition on power up	
25	5g sensor limited to 300Hz	on spring mount	ICS 9881-005-6054-019-0021

Input #	Notes: Filtering	Notes	Sensor
26	5g sensor limited to 300Hz	on spring mount	ICS 9881-005-6054-018-0021
27	5g sensor limited to 300Hz	on spring mount	ICS 9881-005-6054-006-0021
28	5g sensor limited to 300Hz	on spring mount	ICS 9881-005-6054-024-0021
29	20g sensor limited to 500Hz	on suspension upright	ICS 3150-9228-003-020-0224
30	20g sensor limited to 500Hz	on suspension upright	ICS 3150-9211-023-020-0221
31	20g sensor limited to 500Hz	on suspension upright	ICS 3150-9220-001-020-0221
32	20g sensor limited to 500Hz	on suspension upright	ICS 3150-9211-005-020-0221
33	5g sensor limited to 300Hz	on cross member behind driver's seat	ICS 3145-005-2857-042-9632
34	5th order Bessel Filter	Use differential amp before filter (Note 2)	novotechnik SP 2831A502 ART. NR. 001921
35	5th order Bessel Filter	Use differential amp before filter (Note 2)	novotechnik SP 2831A502 ART. NR. 001921
36	5th order Bessel Filter	Use differential amp before filter (Note 2)	novotechnik SP 2831A502 ART. NR. 001921
37	5th order Bessel Filter	Use differential amp before filter (Note 2)	novotechnik SP 2831A502 ART. NR. 001921
38	5g sensor limited to 250Hz	on transmission tunnel between seats	GS Sensors GSA 3206-050505
39	5g sensor limited to 250Hz	on transmission tunnel between seats	""
40	5g sensor limited to 250Hz	on transmission tunnel between seats	""

Input #	A-to-D Channel	A-to-D J3 pin #	Card	Type	Sensor	Vsupply, sensor	Sample Rate (Hz)
RS232 Input		Crossbow Technologies DMU-VGX, ±4 g accels and ±100°/sec rates					
					Accel. X @ apprx C.G.	IMU	133.3
					Accel. Y @ apprx C.G.	IMU	133.3
					Accel. Z @ apprx C.G.	IMU	133.3
					Roll Rate X @ apprx C.G.	IMU	133.3
					Roll Rate Y @ apprx C.G.	IMU	133.3
					Roll Rate Z @ apprx C.G.	IMU	133.3
					Roll Angle @ apprx C.G.	IMU	133.3
					Pitch Angle @ apprx C.G.	IMU	133.3
CAN Bus		Racelogic Vbox GPS					
					Vertical Velocity		20
					Horizontal Velocity		20
					True Heading		20
					Vertical Position (altitude)		20
					Latitude		20
					Longitude		20

Input #	A-to-D Channel	A-to-D J3 pin #	Card	Type
		RS232 Input		
				on transmission tunnel between seats
				on transmission tunnel between seats
				on transmission tunnel between seats
				on transmission tunnel between seats
				on transmission tunnel between seats
				on transmission tunnel between seats
				on transmission tunnel between seats
				on transmission tunnel between seats
		CAN Bus		
			currently used	on roof over Triax accels
			not currently used	on roof over Triax accels
			not currently used	on roof over Triax accels
			not currently used	on roof over Triax accels
			not currently used	on roof over Triax accels
			not currently used	on roof over Triax accels

APPENDIX E - Passive and Test HMMWV Minimum and Maximum Values

MR Passive Vehicle - Lane Change

intended speed	average speed	direction	min/max	roll angle	roll rate	pitch rate	yaw rate	steering angle
15 MPH	15.83	N	MIN	-0.91	-4.37	-1.73	-9.83	-5.69
15 MPH	15.83	N	MAX	1.94	3.91	1.62	9.46	4.47
20 MPH	21.14	S	MIN	-1.21	-4.42	-1.63	-8.21	-3.94
20 MPH	21.14	S	MAX	1.62	3.67	1.42	8.95	3.22
25 MPH	25.09	N	MIN	-1.83	-5.61	-1.23	-12.02	-4.69
25 MPH	25.09	N	MAX	1.72	5.96	1.45	10.03	3.16
25 MPH	26.24	S	MIN	-2.33	-7.73	-0.93	-12.67	-4.80
25 MPH	26.24	S	MAX	1.79	5.18	1.40	11.16	3.41
30 MPH	31.2	N	MIN	-2.06	-5.41	-1.08	-10.37	-3.89
30 MPH	31.2	N	MAX	1.62	7.36	1.16	11.31	3.04
30 MPH	28.85	S	MIN	-2.50	-7.24	-1.54	-12.46	-4.60
30 MPH	28.85	S	MAX	1.67	5.50	1.23	9.59	2.65
35 MPH	35.65	N	MIN	-2.38	-8.03	-1.80	-13.32	-4.23
35 MPH	35.65	N	MAX	2.42	10.23	1.24	11.72	3.06
35 MPH	35.12	S	MIN	-3.13	-7.81	-1.71	-17.27	-5.29
35 MPH	35.12	S	MAX	2.74	13.08	2.23	13.25	3.36
40 MPH	37.91	N	MIN	-2.74	-9.82	-1.56	-13.14	-4.00
40 MPH	37.91	N	MAX	2.69	9.49	1.87	12.61	3.07
40 MPH	38.64	S	MIN	-2.20	-6.95	-1.94	-13.94	-4.30
40 MPH	38.64	S	MAX	2.33	9.76	2.82	12.03	2.96
45 MPH	42.68	N	MIN	-3.05	-10.04	-0.94	-15.30	-4.45
45 MPH	42.68	N	MAX	3.09	14.87	1.67	11.48	2.60
45 MPH	44.57	S	MIN	-2.22	-10.86	-1.66	-15.52	-4.24
45 MPH	44.57	S	MAX	3.52	10.35	1.55	11.96	2.90
50 MPH	48.88	N	MIN	-2.74	-11.42	-2.05	-15.86	-4.17
50 MPH	48.88	N	MAX	3.64	18.25	1.88	14.78	2.85

MR Test Vehicle - Lane Change

intended speed	average speed	direction	min/max	roll angle	roll rate	pitch rate	yaw rate	steering angle
20 MPH	19.6	S	MIN	-1.47	-8.08	-1.35	-16.25	-15.16
20 MPH	19.6	S	MAX	2.26	5.17	1.67	19.40	14.75
25 MPH	23.9	N	MIN	-2.14	-8.36	-0.74	-12.59	-9.79
25 MPH	23.9	N	MAX	1.54	4.60	1.03	16.82	11.54
25 MPH	25.36	S	MIN	-2.04	-6.88	-1.35	-13.92	-10.44
25 MPH	25.36	S	MAX	2.02	6.59	1.14	19.12	12.48
30 MPH	29.99	N	MIN	-2.26	-7.20	-1.08	-12.53	-8.17
30 MPH	29.99	N	MAX	1.99	6.05	1.65	19.44	11.25
30 MPH	29.68	S	MIN	-2.54	-9.88	-1.05	-14.12	-9.37
30 MPH	29.68	S	MAX	2.08	4.64	1.23	18.73	10.85
35 MPH	33.77	N	MIN	-2.50	-8.20	-1.71	-14.99	-8.94
35 MPH	33.77	N	MAX	2.38	10.18	1.50	20.30	11.35
35 MPH	33.15	S	MIN	-2.48	-9.83	-1.32	-16.35	-9.82
35 MPH	33.15	S	MAX	2.47	9.00	1.56	16.13	8.55
40 MPH	38.95	N	MIN	-3.09	-8.81	-1.30	-13.81	-8.16
40 MPH	38.95	N	MAX	2.51	9.36	1.56	20.43	10.84
40 MPH	38.13	S	MIN	-3.20	-16.70	-1.46	-23.23	-13.53
40 MPH	38.13	S	MAX	3.59	11.88	1.56	20.45	10.97
45 MPH	44.26	N	MIN	-3.75	-18.21	-2.76	-20.91	-10.91
45 MPH	44.26	N	MAX	3.66	17.88	2.31	22.95	12.16
45 MPH	46.6	S	MIN	-3.46	-17.77	-3.37	-17.43	-11.32
45 MPH	46.6	S	MAX	3.37	14.04	1.25	22.36	10.69
45 MPH	44.53	N	MIN	-3.35	-17.27	-2.75	-18.64	-10.58
45 MPH	44.53	N	MAX	3.25	14.19	0.81	25.52	12.67
50 MPH	49.82	S	MIN	-5.13	-29.52	-4.60	-25.09	-14.54
50 MPH	49.82	S	MAX	3.81	12.95	2.23	33.44	14.93
50 MPH	49.67	N	MIN	-4.69	-23.54	-4.59	-29.40	-13.06
50 MPH	49.67	N	MAX	4.41	24.58	1.50	30.09	13.91